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Institute of Polar Studies

Report No. 42

A 200-Year Record of Glacier Mass Balance at Deception Island, Southwest Atlantic Ocean, and Its Bearing on Models of Global Climatic Change

by

Olav Orheim
Institute of Polar Studies

September, 1972

The Ohio State University
Research Foundation
Columbus, Ohio 43212

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ABSTRACT

Subglacial volcanic eruptions on Deception Island (63°S, 60° 40'W) in 1969 and 1970 revealed ice stratigraphy in fissures and craters. Annual net mass-balance variations from about 1780 A.D. to the present were determined from this stratigraphy. Annual layers were exceptionally well marked by dirt layers, formed each summer when large amounts of dust are blown onto the glaciers from surrounding areas of loose volcanic material. No dust is deposited on the glaciers in the winter because the island is then completely snow-covered. The sections studied originated high in the accumulation area of the glacier, and only minor errors in the record are caused by years missed due to zero or negative net balance.

Meteorological data are available from Deception Island from 1944 to 1967; summer degree-days for these years are significantly negatively correlated with stratigraphically determined net mass balances ($r = -0.55$, $P < 0.01$). This correlation generally becomes insignificant when dating of the layers is changed by one or more years and thus provides a confirmation of the stratigraphic technique. The correlation also shows that summer degree-days and summer balances must be closely correlated; year-to-year variations in the summer balances, as represented by the summer degree-days, account for a larger proportion of annual net balance variations than do winter balance variations. Close correlation between summer degree-days and summer balances is supported by heat- and mass-balance results on a selected glacier on the island.

This glacier was in mass equilibrium for the 1968-1969 balance year but had negative mass balances for the following two years. Shortwave solar radiation contributed most of the heat transfer to the glacier in the summer. Mean gradients with respect to elevation of the summer, winter, and net balance curves are 6, 1, and 7 mm m^{-1}, respectively. The term "mean activity index" is proposed for the latter gradient, and its use is suggested in place of Shumskii's "energy of glacierization" and Meier's "activity index".

The stratigraphic studies revealed 23 probable volcanic eruptions since 1780. Although these eruptions have changed significantly the mass and heat balance conditions in the ablation area of the glaciers, their effects were not significant in the accumulation areas, where the ash is buried within a year.

Comparisons between summer temperatures at Deception Island and those of 14 other stations in middle to high latitudes in the southern hemisphere show that summer temperature variations at Deception Island are representative of regional variations in the southwest Atlantic Ocean.

Mean mass balances for 5-year intervals, and 5-year running means of balances for Deception Island are significantly negatively correlated with observed mass-balance variations from 1946 in the northern hemisphere, and balances in both hemispheres show a marked cyclicity of about 10 years. The same antiphase relationship, with a cycle of 11 years, and a weaker cycle of about 20 years, is found when the entire Deception record is compared with the precise record back to 1816 from Storbreen, Norway.

The entire Deception Island record shows the same general atmospheric warming from the 19th to the present century, as occurred in the northern hemisphere and in lower to middle latitudes of the southern hemisphere.

Models proposed to explain climatic changes must account for a global warming from late last century to about 1940, and an antiphase cyclic relationship, characterized by dominant periods of about 11 and about 20 years, in the climatic elements that affect glacier mass balances in middle to high latitudes in the two hemispheres.

ACKNOWLEDGMENTS

This research was carried out in the four austral summers from 1968-1969 to 1971-1972. It was supported by National Science Foundation grants GA-4233, GA-14733, GV-26133, and GV-28895, which were administered by The Ohio State University Research Foundation. I am most indebted to Dr. Colin B. B. Bull, who generated the first of these research proposals, supervised the projects, and provided guidance both in the field and during the preparation of this dissertation.

I am also very grateful to Dr. Jean-Roland Kläy, who was co-principal investigator with me for the first two years of this project, and to Dr. Charles H. Shultz, who carried out associated geological studies for two seasons at Deception Island, for their cooperation in the field and for many stimulating discussions.

I am indebted to Dr. Valter Schytt, who participated during one season as a Research Associate, and who gave many very helpful comments on the research both in the field and during his one-year stay at The Ohio State University.

Field assistance was provided by Mr. Fleetwood R. Koutz, Jr., Mr. Kent W. Densing, Mr. Robert D. Ellis, Dr. Terence J. Hughes, Mr. James E. Curl, and Mr. Michael J. Quinn. Without their willing help this research could not have been accomplished.

Field support was provided largely by the U.S. Antarctic Research Program (USARP), and I am very grateful to the USARP representatives and the various crews and officers of R/V Hero and of several U.S. Coast Guard icebreakers which also gave logistic support.

For three seasons the expeditions were based on the Argentine station and I want to thank the Argentine Navy for opening these facilities to us, and for providing logistic support, including transportation between South America and Deception Island on several occasions.

Free computer time was provided by the Instruction and Research Computer Center, The Ohio State University. I am indebted to Dr. Charles E. Corbató and Mr. Ian M. Whillans who assisted with the computer programming, and to Dr. John N. Rayner, who placed his cross-spectral analysis program at my disposal.

Use of a Wild B-8 plotter was provided by the Department of Geodetic Science, The Ohio State University, and I am very grateful to Mr. Henry H. Brecher, who constructed maps of selected features on Deception Island, and who also commented on an early version of this dissertation.

I gratefully acknowledge the use of the office and laboratory facilities of the Institute of Polar Studies, The Ohio State University, and the excellent support of the various members of the Institute, and in particular the help given me by Mr. John F. Splettstoesser, Associate Director, and Mr. Herbert S. Mehrling, Technical Research Associate. Mr. D. A. Porter drafted the figures.

The manuscript was typed by Mrs. Jean Cothran, and it was critically reviewed by Drs. Colin B. B. Bull, Charles E. Corbató, John N. Rayner, and Valter Schytt.

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Statement of Problem

Subglacial volcanic eruptions in 1969 and 1970 on Deception Island in the southwest Atlantic Ocean (63°S, 60° 40'W) have exposed the annual glacier stratification in a 50-m-deep fissure and a 100-m-deep crater. The precise mass-balance history for these glaciers for the past 200 years was determined in the 1969-1970 and 1970-1971 field seasons by analysis of these stratigraphic sections. This record is one of the longest continuous records in the southern hemisphere of variations of climatic parameters, and between latitude 55° and 65°S is the only record extending into past centuries.

Two basic questions investigated in this report are: 1) does the record of mass-balance changes reflect variations in regional climate and, in this connection, what region is represented, and which climatic elements are reflected; 2) if the first question can be answered, can a comparison of the Deception Island record with records from other areas provide information that can be used to test models that have been proposed to explain past climatic changes?

These questions are investigated as follows: 1) the net mass-balance record from the crater and fissure sections is presented, and the uncertainties in the record are discussed; 2) effects of volcanic eruptions on the mass-balance record are considered; 3) present heat- and mass-balance conditions of the glaciers on the island are presented; 4) the relationship is discussed between mass-balance variations and climate for the period in which meteorological observations have been made at Deception Island; 5) meteorological data for Deception Island are compared with those from other stations in the southern hemisphere; 6) the net mass-balance record is compared with other records of net mass-balance variations; 7) climatic elements that contribute most to the mass-balance variations are compared with records of these elements from other areas; 8) and lastly, some models of past climatic change are considered in view of the results from the two above-mentioned comparisons.

Background

Deception Island is the southernmost of the South Shetland Islands, situated 100 km north of the Antarctic Peninsula. It is a horseshoe-shaped volcanic island, 14 km by 13 km, enclosing the large flooded caldera named Port Foster (Fig. 1). The island attains elevations of 450 m and 550 m on the southwest and east sides; these parts of the island are mostly glacier covered.

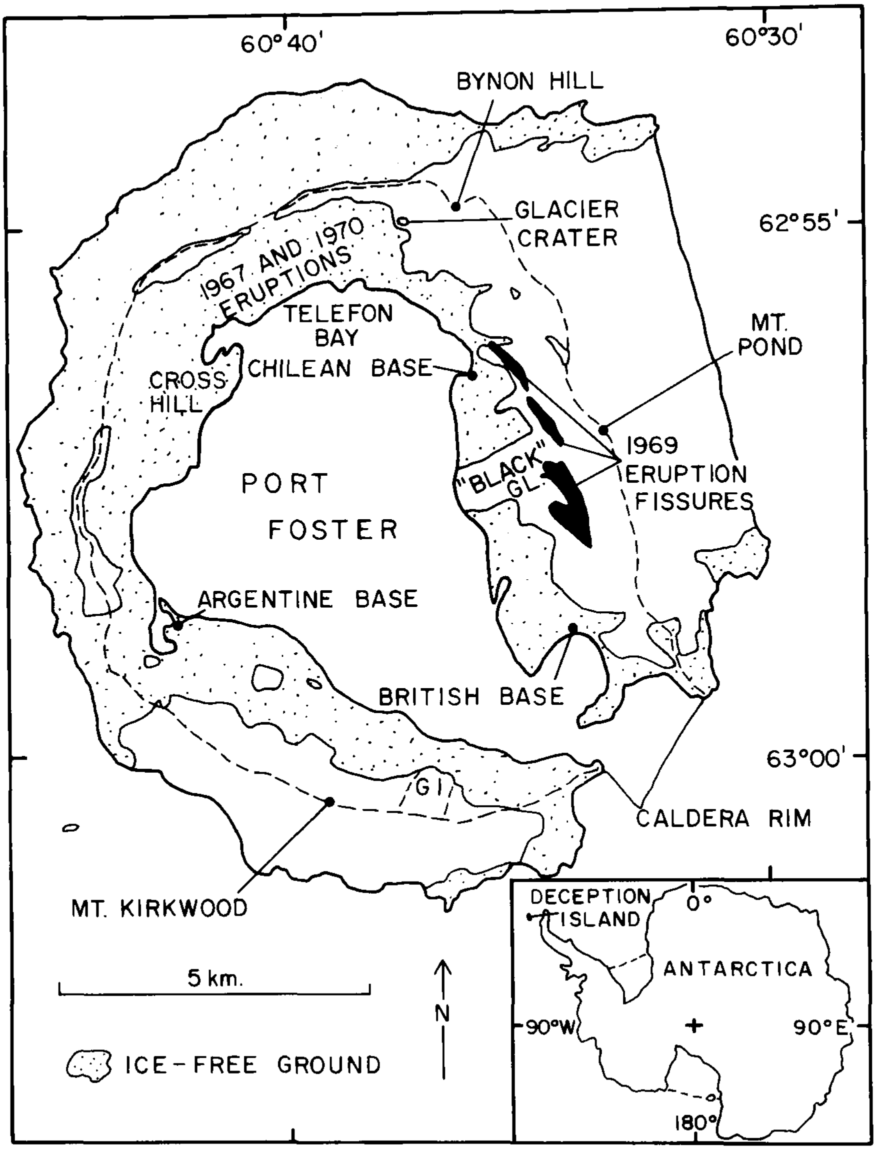

Figure 1. Index map of Deception Island, with location of glacier G 1, and recent eruptions.

Port Foster is an excellent harbor, where a whaling station was operated in the summers from 1911-1912 to 1915-1916 and from 1920-1921 to 1928-1929. The first year-round station was established in 1944 by the British. Argentina followed with a station in 1948, and Chile in 1955. All stations were operated continuously until December 1967, when they were closed following an eruption described below.

The earliest historic volcanic eruption took place in 1842 from vents in the southwest part of the island on the lower slopes of Mt. Kirkwood (Wilkes, 1845). This account was doubted by later workers (Andersson, 1906, p. 49; Adie, 1957, p. 506), as, apart from fairly intense fumarolic activity, no other volcanic activity had been observed. The veracity of the account of the 1842 eruption is affirmed in this study. In December 1967, however, an eruption formed a new island in Telefon Bay and an associated eruption occurred on land north of Pendulum Cove (site of the Chilean base). This was followed in February 1969 by a fissure eruption that cut through the glacier on the western flank of Mt. Pond. The volcano erupted again in August 1970, affecting the lower part of the caldera wall from Cross Hill to the foot of Bynon Hill. The island formed in Telefon Bay in 1967 was joined to the main island by a new strip of land, and an oval-shaped crater, 300 m by 200 m, was blown through the lower parts of a glacier on the western flank of Bynon Hill.

The three recent eruptions were entirely explosive in nature. Most of the earlier eruptions were also explosive, both those detected in this study and those that generated the bulk of the material forming the island. Hence the island is composed mainly of pyroclastic rock, primarily yellow tuffs, with only minor amounts of highly viscous lava. Most rocks are basaltic to andesitic in composition, and almost all of them have glassy or aphanitic textures. Porphyritic rocks are rare and phaneritic rocks are virtually absent (Shultz, 1970, p. 97). However, outcrops are scarce because the island is covered by glaciers and snowfields over half the surface area, and by extensive areas of cindery scree and glaciofluvial deposits.

The present climate of Deception Island can be characterized as polar maritime based on data in Pepper (1954), Schwerdtfeger and others (1959), and U.S. Weather Bureau (1968). The mean annual temperature near sea level is -2.9°C, and the mean monthly temperatures vary from +1.2°C in January to -8.4°C in August. The diurnal variation is small, averaging 2°C in summer, December through February. The maximum temperature normally exceeds 0°C on some days in even the coldest months.

The prevailing winds are from the northeast and from the westerly sector (southwest to northwest), whereas most storms are from the northeast. Winds from the south and southeast are rare. Mean monthly wind speeds vary from 5 m s^{-1} in summer to 7 m s^{-1} in winter.

The annual precipitation is 500 to 1000 mm. Most of the precipitation falls as snow in the spring and autumn, and is probably mainly associated with the northeast winds. However, precipitation data are incomplete and unreliable because of drifting snow, and, as shown by Swithinbank (1957) for Maudheim on the Antarctic coast (71°S, 11°W), cannot be used to determine the accumulation. The combined effects of imprecise precipitation measurements and local variations in the amount of precipitation caused by topographic differences are illustrated by the insignificance of the correlation between the total monthly precipitation values reported for the Argentine and British stations, separated by 6 km. Using all available pairs (16) of data, the correlation coefficient, $r = +0.35$, and the probability, $P, > 0.15$. In contrast, the correlation between the mean monthly temperatures of the two bases is highly significant ($r = +0.98$, $P, < 0.001$, for 84 pairs of data from seven arbitrarily selected years in the 1950's).

The relative humidity in summer averages 85-90 percent and the cloud cover averages eight-tenths to nine-tenths. Incoming shortwave radiation in the summer averages about 10,000 kJ $m^{-2}d^{-1}$.

The glaciological investigations described here started in the 1968-1969 austral summer, and continued in the field during the following two summers. The main part of the work has been a reconstruction of the net mass balance and climatic history of the area, by studies of the ice stratigraphy exposed in a fissure and crater formed through the two glaciers by the 1969 and 1970 eruptions. In addition detailed mass-balance studies, some heat balance studies, and glacier strain studies were carried out on glacier G 1 (Fig. 1), and less precise mass-balance studies were conducted on several other glaciers on the island and on Rotch Ice Dome, Livingston Island, 30 km north of Deception Island.

Previous Work

No glaciological studies were undertaken on Deception Island prior to this work, although there have been numerous geological investigations. The earliest detailed description is that of Kendall (1831), who visited the island in 1829 and measured fumarole temperatures. Johnson (Wilkes, 1845, p. 148) observed the fumaroles in 1839, and Smyley (Wilkes, 1845, p. 149) stated that in 1842 the "whole south side of Deception Island appeared as if on fire," and he "counted thirteen volcanoes in action." There seems little reason now to doubt this account, as volcanic deposits in the glacier ice are dated stratigraphically to within a few years of 1842 (Orheim, in press, b).

The first geologist to visit Deception Island was Andersson, in 1902, with the Swedish Antarctic Expedition. Andersson lost his collection of specimens when the expedition's support vessel, Antarctic, was shipwrecked, and he gave only a brief description of the island, mainly quoting earlier visitors (Andersson, 1906). Gourdon (1914), who participated in the second French Antarctic Expedition (1908-1910), gave a brief description of the petrography and contributed the first chemical analyses. Both he and Andersson commented on the large amounts of fine ash that was lifted from the surface by the wind. Ferguson (1921, p. 44) observed, on his visit in 1913, that the glaciers were less extensive then than formerly.

The most important of the early works is by Holtedahl (1929), who visited the island in 1928 with the Norwegian Antarctic Expedition. He suggested that the island was a caldera, the central bay being formed by subsidence of a volcano along circular faults. He divided the lavas and agglomerates into an Older and a Younger Volcanic Series, separated by the formation of the caldera. Barth and Holmsen (1939) described the rocks collected by Holtedahl, published chemical analyses and optical data on the mineralogy of the lavas, and noted the abnormally high soda content of the suite.

Olsacher (1956) published a geological map of the island at a scale of 1:68,730 and restated Holtedahl's interpretation of the structure and stratigraphy of the island. Hawkes (1961) also published a geological map of the island, at a scale of 1:25,000, and provided by far the most comprehensive study of the island. He discussed in detail the petrology of the rocks, considering the rock suite to be a local alkaline deviation from the normal andesite-rhyolite association of the South Shetland Islands. Hawkes suggested that the caldera was formed by subsidence of a group of overlapping volcanoes along arcuate radial faults, an interpretation that has not been favored by more recent studies. He divided the rocks into one pre-caldera group, and three post-caldera groups, and presented further chemical analyses.

A large number of accounts have appeared following the three recent eruptions, and only the more important geologic studies will be mentioned. Valenzuela and others (1968) and Clapperton (1969) described the 1967 eruption. Baker and others (1969) discussed the 1967 and 1969 eruptions, and presented further chemical analyses. Shultz (1970) discussed the geology of the island, and collected samples for radiometric dating of the different rock groups, which have all been dated to be younger than 100,000 years (R. J. Fleck, personal communication, 1971). Baker and McReath (1971) described the 1970 eruption and chemical analyses of ejected bombs. Gonzáles-Ferrán and others (1971) also presented chemical analyses of the 1970 eruption, and discussed the chemical evolution of the volcano. Orheim (in press, a) presented evidence for volcanic eruptions early in this century, and chemical analyses of rocks of two of these eruptions. Faure and others (1971) described the isotopic composition of strontium in the volcanic rocks.

A few studies have analyzed the meteorological records from Deception Island. Continuous records of surface observations are available from 1944 to 1967, except for the records from January 1946 to January 1947 which were lost in a fire at the British station. Pepper (1954) analyzed the records for the British station from 1944 to 1950. Schwerdtfeger and others (1959) analyzed the observations at the Argentine station from 1948 to 1956. Giles (1971) presented the sunshine records for the British station from 1947 to 1966. Limbert (1969) discussed the meteorological conditions prevalent during the 1967 eruption.

VARIATIONS IN MASS BALANCE FROM ABOUT A.D. 1780 TO THE PRESENT

Stratigraphic Sections, Criteria, and Techniques

The glacier stratigraphy exposed by the 1969 and 1970 eruptions provides an exceptionally good opportunity for determining the past net mass-balance variations at Deception Island. The mass-balance history for this century was determined in 1970 by studies on the southernmost of the glacier fissures formed in 1969 (Figs. 1 and 2). This fissure is situated at an elevation of about 400 m in the accumulation area of "Black" Glacier, where the mean elevation of the equilibrium line is 200-250 m (Fig. 3). In the following season the mass-balance history was extended to about A.D. 1780 by studies of the upper half of the glacier section exposed in a crater formed by the 1970 eruption through the ablation area of the glacier flowing from Bynon Hill (Fig. 1). This glacier has a simple flow pattern that has not disturbed the orderly arrangement of the annual layers (Fig. 4). Flow-line considerations show that the ice in the section originated mostly at 300-350 m elevation, about 100 m higher than the mean elevation of the equilibrium line (Fig. 5).

The annual layers are recognizable by the dirt layers. One dirt layer is formed each year in the accumulation area of the glaciers when the summer surfaces, dirty from windblown dust, are buried by the clean winter snow. These summer surfaces are very well developed on the Deception Island glaciers, because about half of the island is covered by loose volcanic material in summer. Albedos as low as 0.3, caused by windblown dust, were recorded on snow surfaces at 400 m elevation in late summer. The island is normally completely covered by snow from March to November/December, so that the balance year marked by the dirt layers is considered to extend from February to February.

The summer surfaces exposed in the sections are mostly 0.1- to 0.02-m-thick layers of scattered particles in clean or very slightly colored ice. The largest particles were approximately 0.1 mm in diameter. The dirt concentration in the layers is estimated to be mostly between 0.1 and 1 percent.

The stratigraphic studies were made on vertical sections formed by cleaning off the near-surface ice from the walls. The sections were usually 1 or 2 m wide, but were widened further in a few places where the interpretation of the stratigraphy in the narrow section contained uncertainties, and in a few places where the layer thickness showed large lateral variations. The extent of lateral thickness variations was established by following the layers across the ice walls. Once a layer was recognized in the freshly exposed sections it could usually be easily recognized in the unexposed areas because of differential ablation.

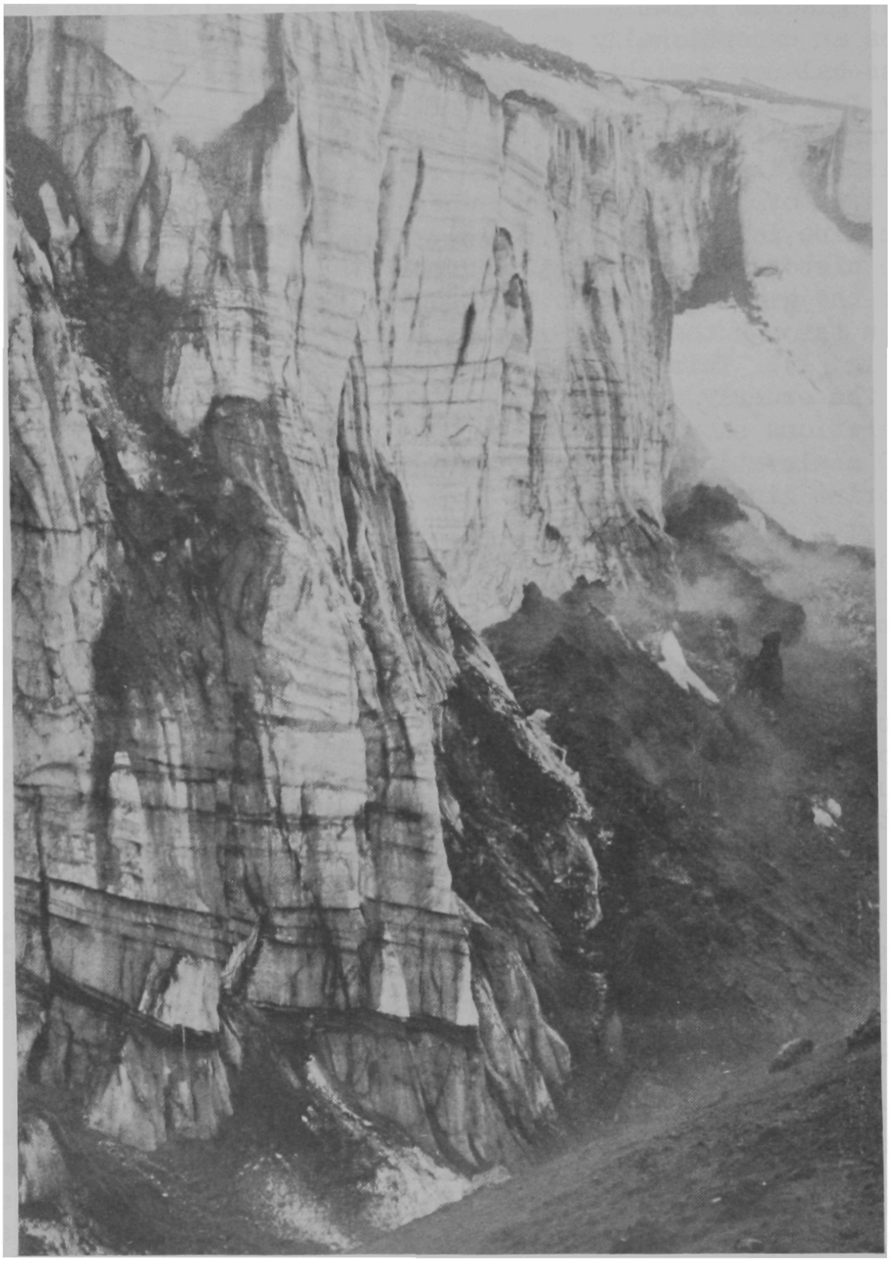

Figure 2. The southernmost of the glacier fissures formed by the 1969 eruption. The ice cliff is about 40 m high. The dark layers near the base of the cliff are volcanic deposits from eruptions in early part of this century.

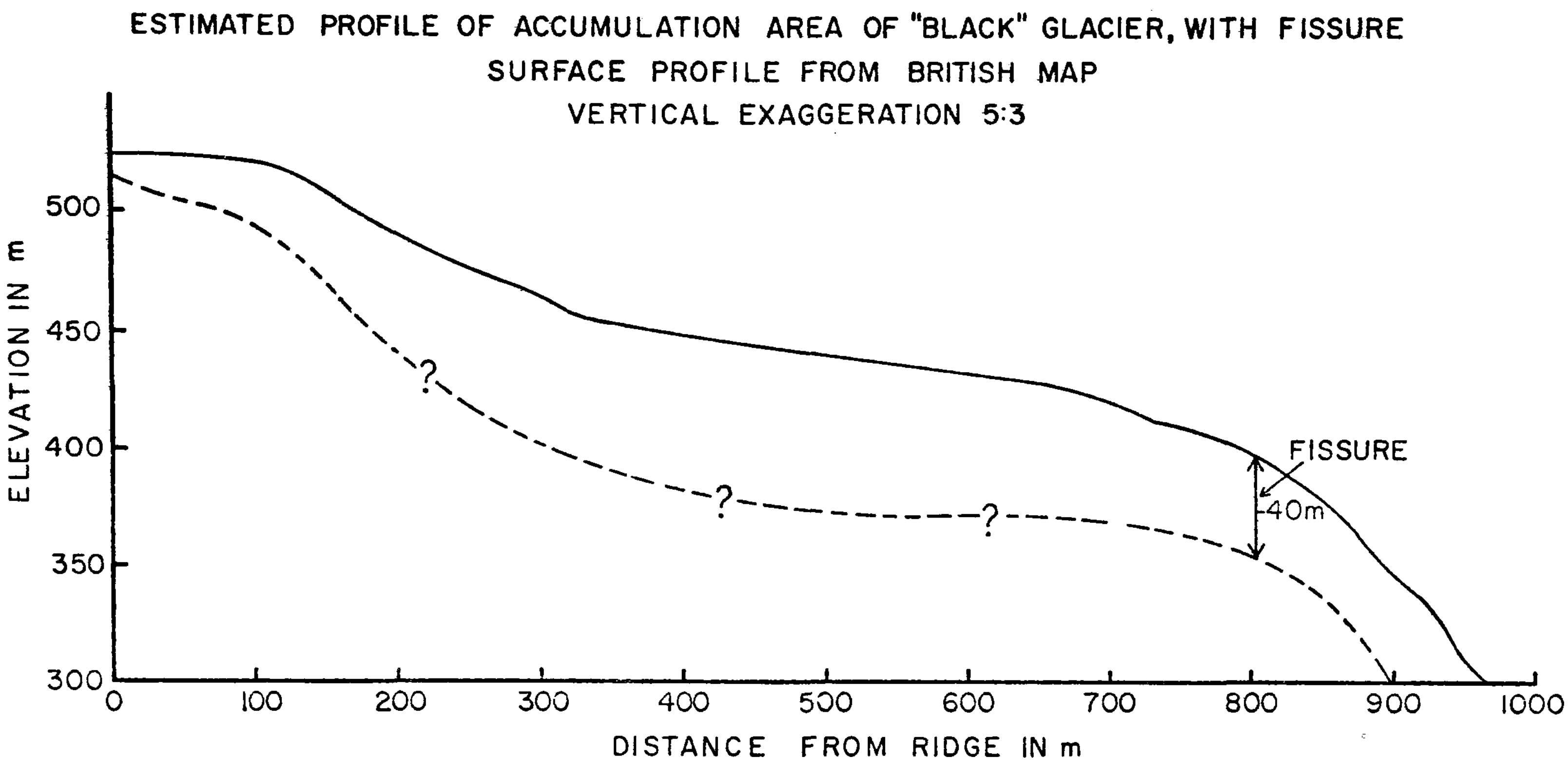

Figure 3. Estimated profile of the accumulation area of "Black" Glacier, with indicated location of the fissure.

Figure 4. Upper part of the glacier crater formed by the 1970 eruption. The ladder indicated by arrows is about 20 m long. The lower end of the ladder is at an eruption layer from about 1780. The dark material 10 m above the top of the ladder is possibly slumped volcanic material from the 1842 eruption.

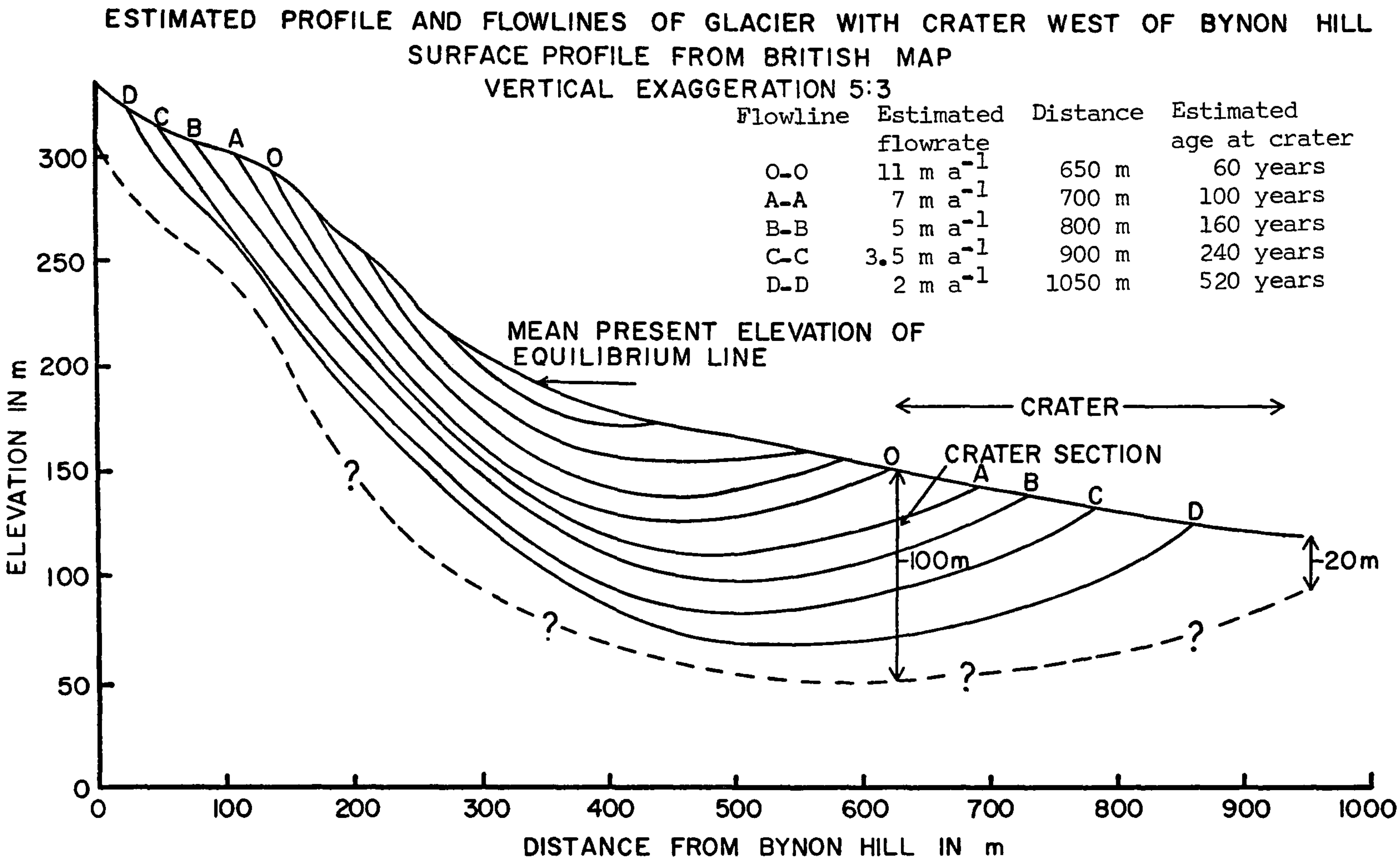

Figure 5. Estimated profile and flowlines of glacier west of Bynon Hill, with approximate location of crater. The indicated flow rates are approximate and are based on velocity measurements on glacier G 1, adjusted for lower slopes on the depicted glacier. The flow rates, if in error, are most likely to be too large.

ERRATA

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Olav Orheim

p. 11	New page provided
p. 19, first paragraph, last line	Should read discussed on pages 24 to 28
p. 36, line 4 from bottom	Should read climatic effects
p. 39, paragraph 3, line 7	Should read last two summers
p. 55, paragraph 3, line 6	Should read The ice in the fissure section, recorded as deposited
p. 59, paragraph 3, line 3	Should read limited, noticeable patterns
p. 72, paragraph 1: line is missing	Insert between lines 3 and 4 whereas those from the southern hemisphere are measured on the glaciers
p. 75, last line	Should read (see p. 72).
p. 77, last line	Should read (see p. 72).
p. 79, paragraph 2, line 5	delete running
p. 79, paragraph 2 line 6	Should read are weakly negatively correlated.
p. 92, paragraph 5, line 2	Should read models will now be considered
p. 95, paragraph 2, lines 12-13	Should read island and agree also with
p. 118, Troitskiy reference	Should read Troitskiy, L. S.,

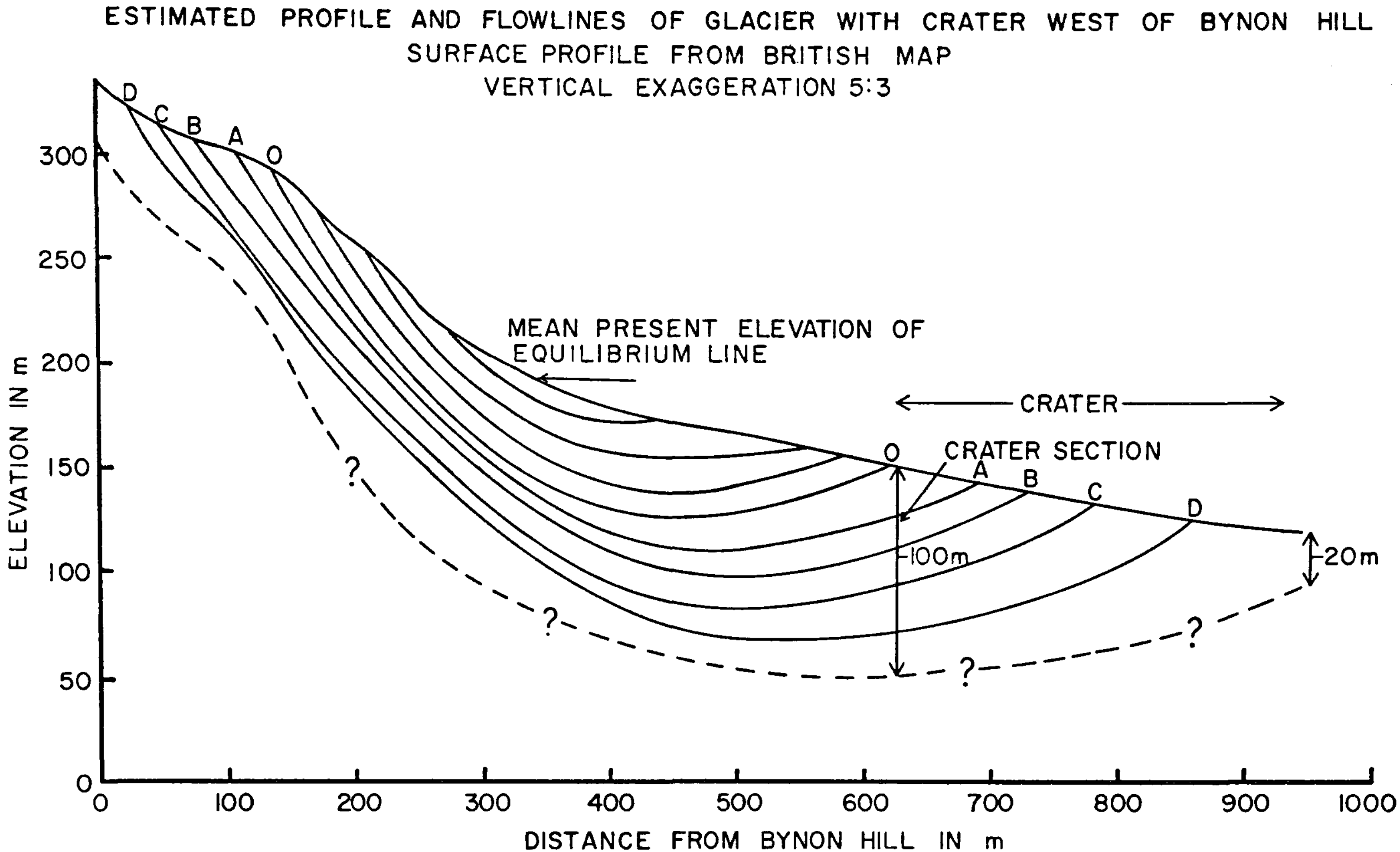

Figure 5. Estimated profile and flowlines of glacier west of Bynon Hill, with approximate location of crater. The indicated flow rates are approximate and are based on velocity measurements on glacier G 1, adjusted for lower slopes on the depicted glacier. The flow rates, if in error, are most likely to be too large.

The thickness of all layers was measured at right angles (by eye judgment) to the plane of the layers. Each thickness value was based on a minimum of 2 or 3 measurements, and several more were made in cases where the thickness varied laterally.

There was a lateral displacement of the measured fissure section, parallel to the plane of the layers, of about 100 m. This displacement was mostly along a single layer at about 36.4 m depth (Fig. 6). There was also a gradual lateral displacement of a few tens of meters over the section between depths of about 5 to about 30 m, because this part of the stratigraphy was accomplished by following the edge of a large, steep snowbank. In addition there were a few short lateral displacements at various other places in the section.

There were only small lateral displacements in the crater section, because it was studied along an approximately vertical line at about right angles to the plane of the layers. This work was done with the aid of ropes and a 25-m-long crevasse ladder.

The densities of the fissure section were determined continuously for the upper 4 m, and by spot measurements of several samples each at depths of 15 and 35 m. The density was 0.78 Mg m^{-3} at 15 m, corresponding to nearly impermeable ice. This value was confirmed by the observation that meltwater colored by the 1969 eruption material reached impermeable ice at about 17 m depth.

The crater section consisted of solid ice throughout, to which a uniform density of 0.9 Mg m^{-3} was ascribed.

The rate of progress in the stratigraphic studies was about 1 vertical meter per hour. The stratigraphic studies were all done by the author. The stratigraphic sections are presented in Figs. 6 and 7, and the deviations of the measured net mass balance from the mean, and the 10-year equal-weighted running means of the net balances are presented in Figs. 8 through 11. All net mass balances are presented as meters of water equivalent, found by multiplying the layer thickness by the density for each layer. The values of layer thicknesses, densities, and net balances for individual years for both records are given in Appendix A.

The mean annual balance of the fissure record is 0.47 m, with a standard deviation, σ, of 0.27 m, and the crater record has a mean of 0.39 m, with $\sigma = 0.26$ m. The preserved net balance varies from 0.10 to 1.33 m for the fissure, and from 0.05 m to 1.36 m for the crater. These are not necessarily the total ranges of variations, as there may be years with net balance ≤ 0 (see below). Expressed as variations in the elevation of the equilibrium line these net balance variations correspond to a total range of about 200 m.

FISSURE STRATIGRAPHY, DECEPTION ISLAND

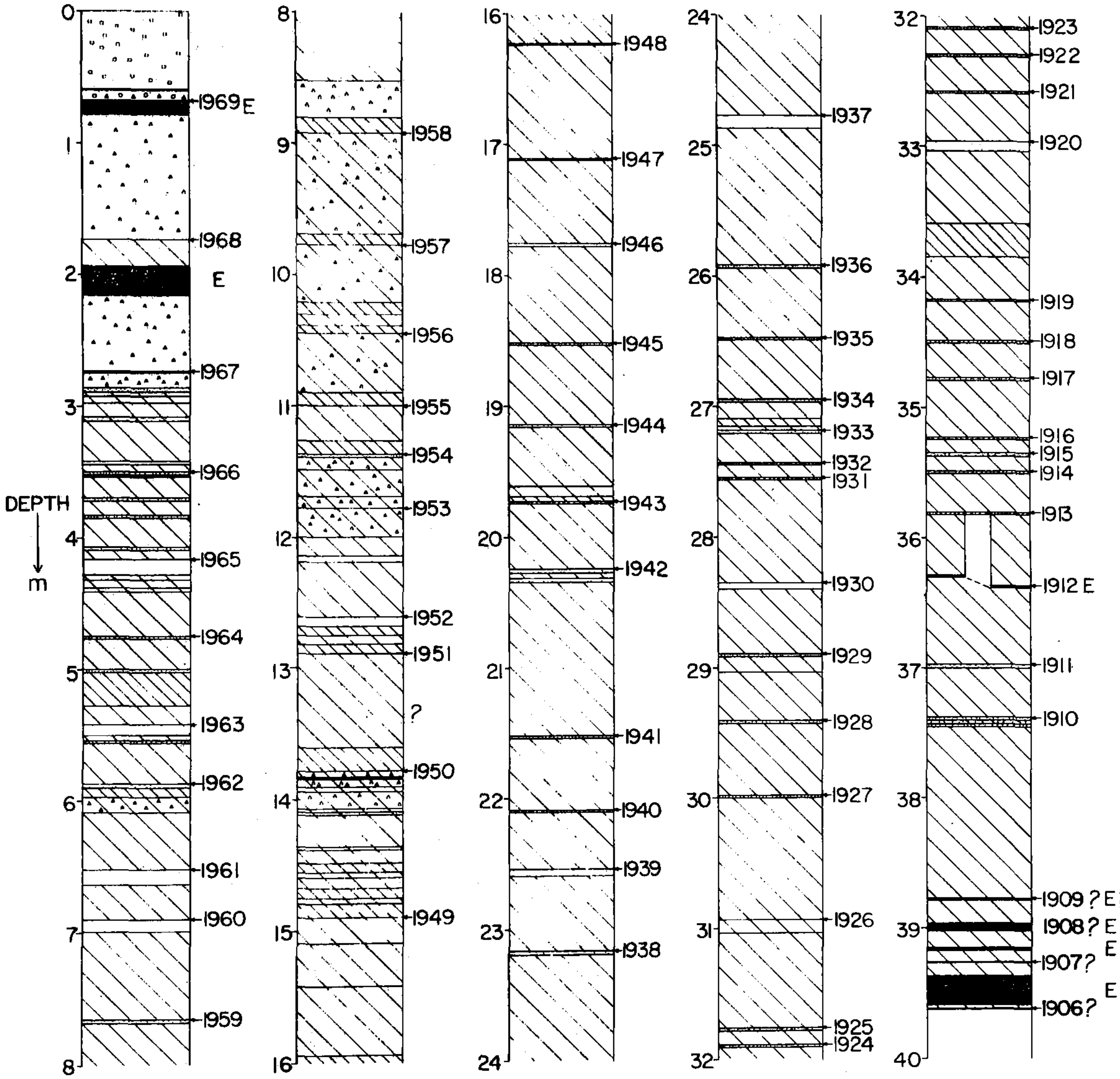

Figure 6. Simplified stratigraphy of ice fissure. Open circles represent snow, triangles represent firn, close hatching represents bubble-free ice, and open hatching represents bubble-filled ice. For other symbols see Figure 7.

GLACIER CRATER STRATIGRAPHY

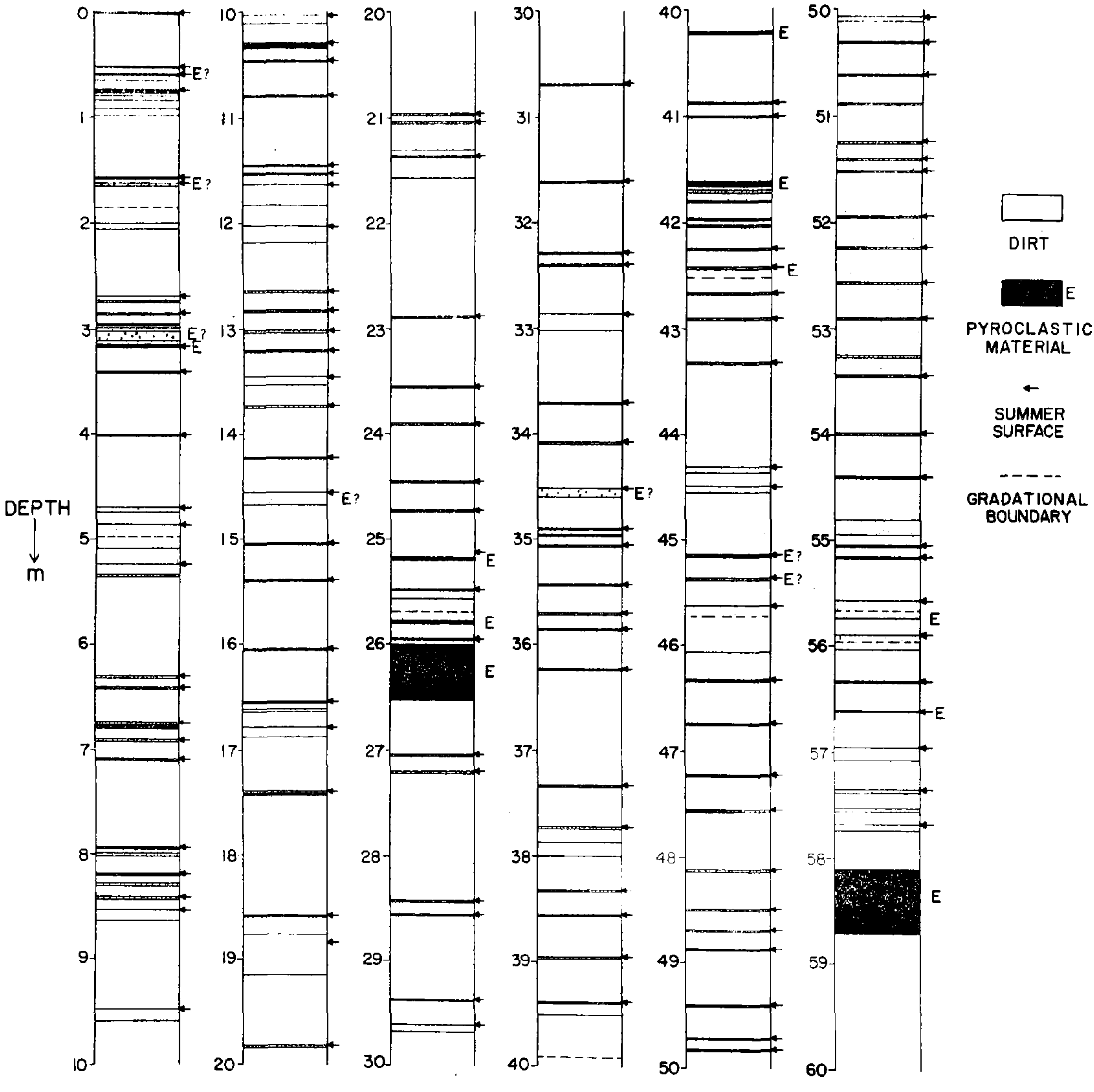

Figure 7. Simplified stratigraphy of upper part of glacier crater. The eruption layers are marked with "E".

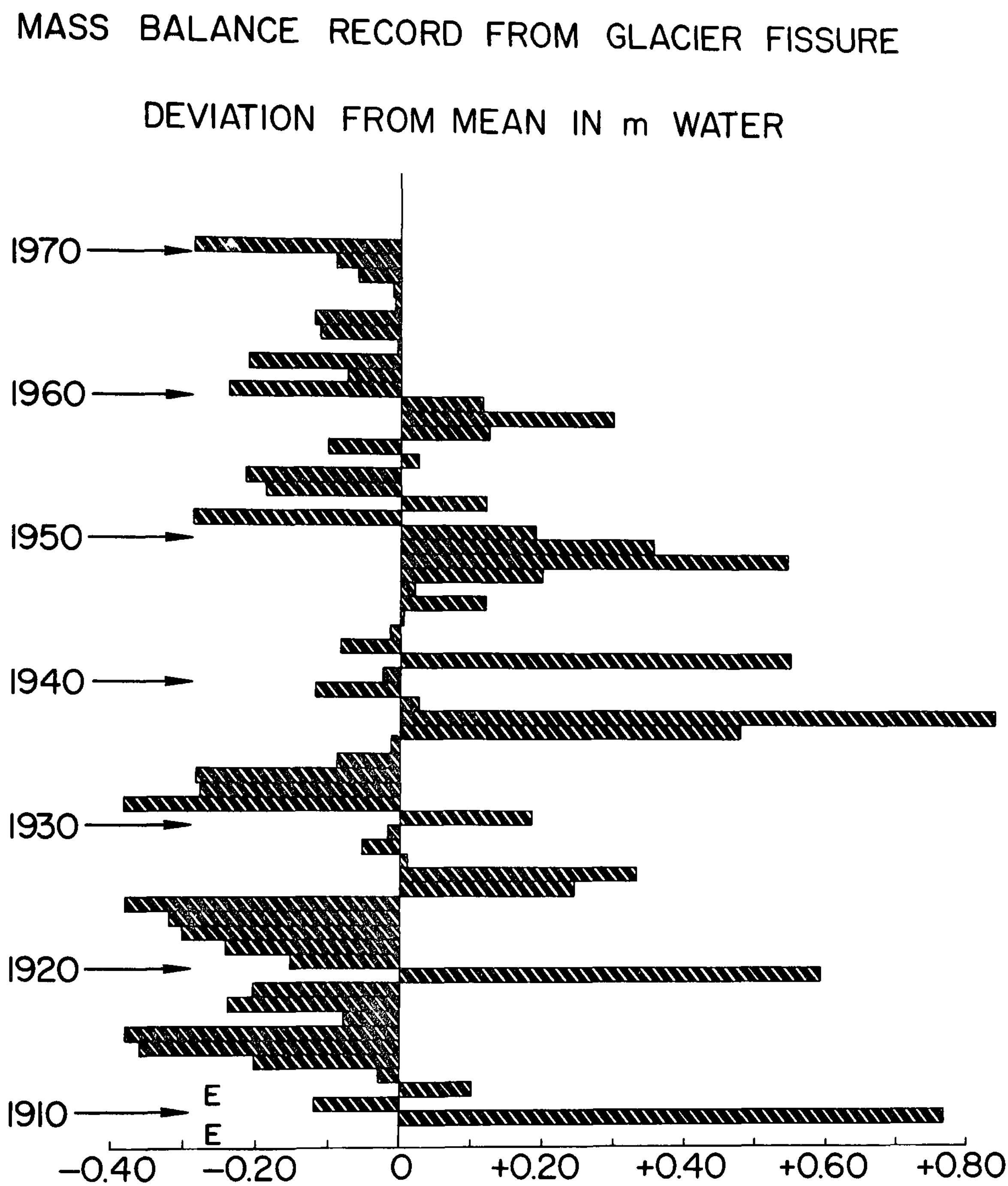

Figure 8. Deviations from mean (0.47 m) of fissure mass balances. "E" represents eruptions.

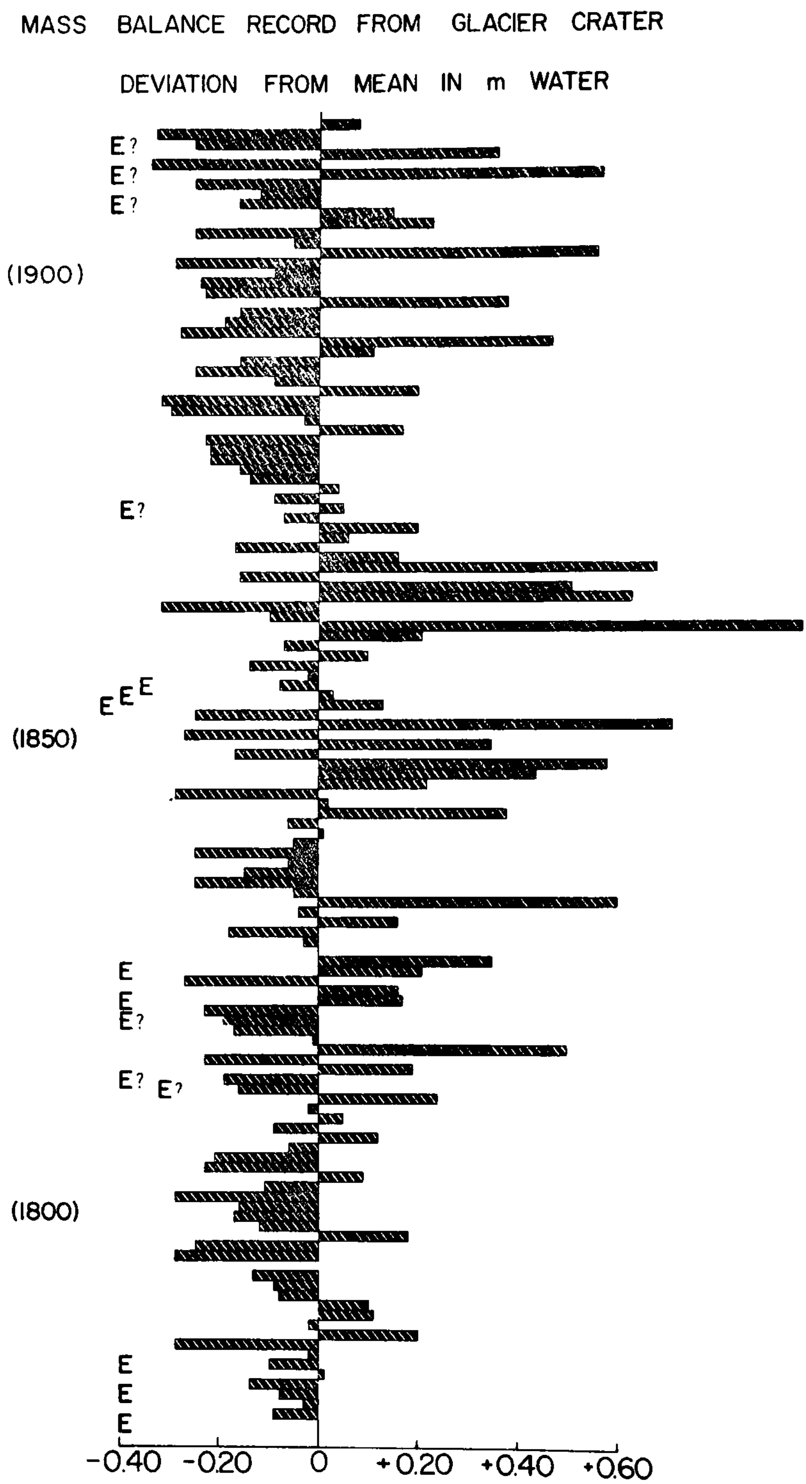

Figure 9. Deviations from the mean (0.39 m) of crater mass balances. "E" represents eruptions.

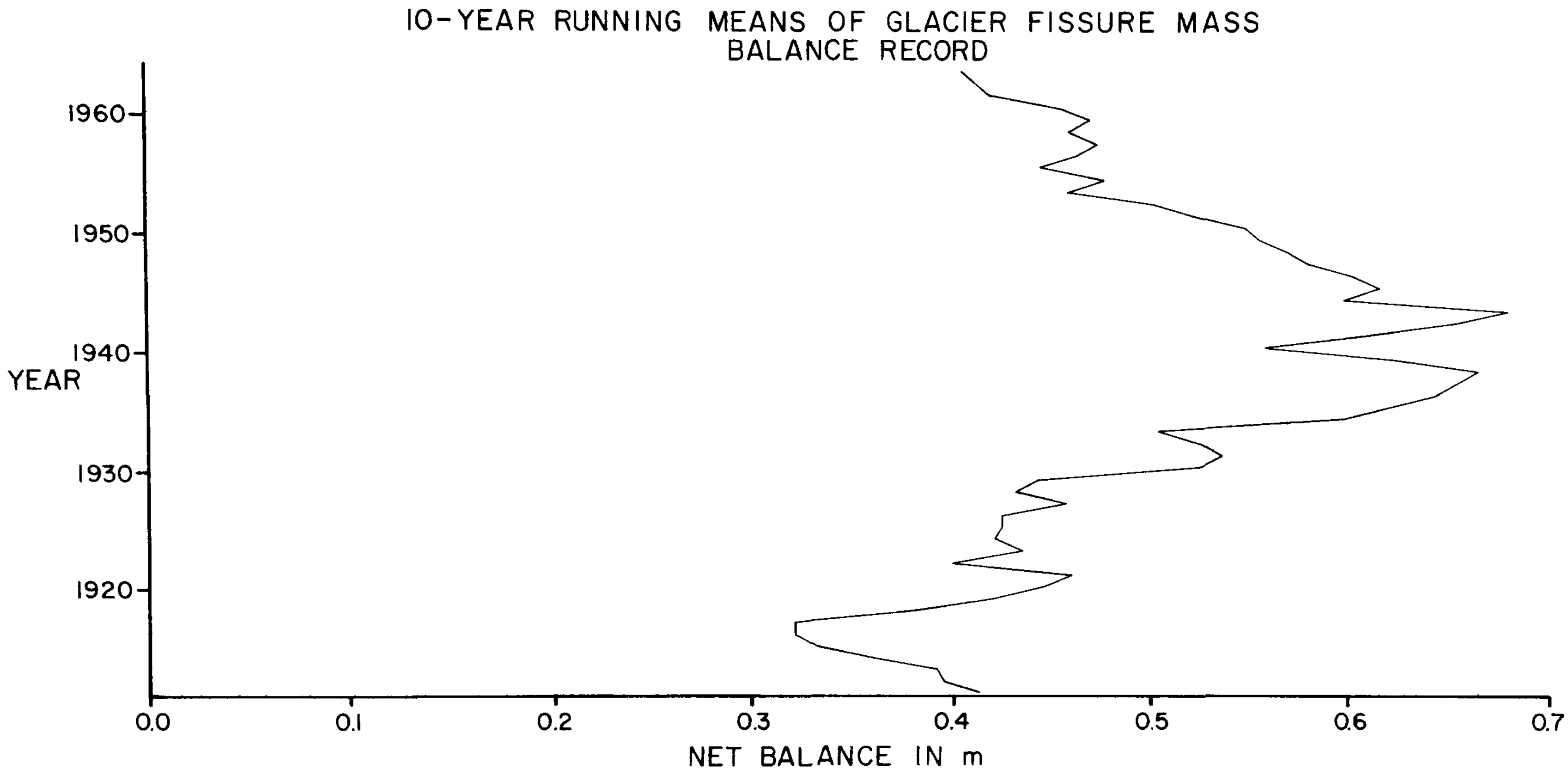

Figure 10. 10-year equal-weighted running means of fissure mass balances.

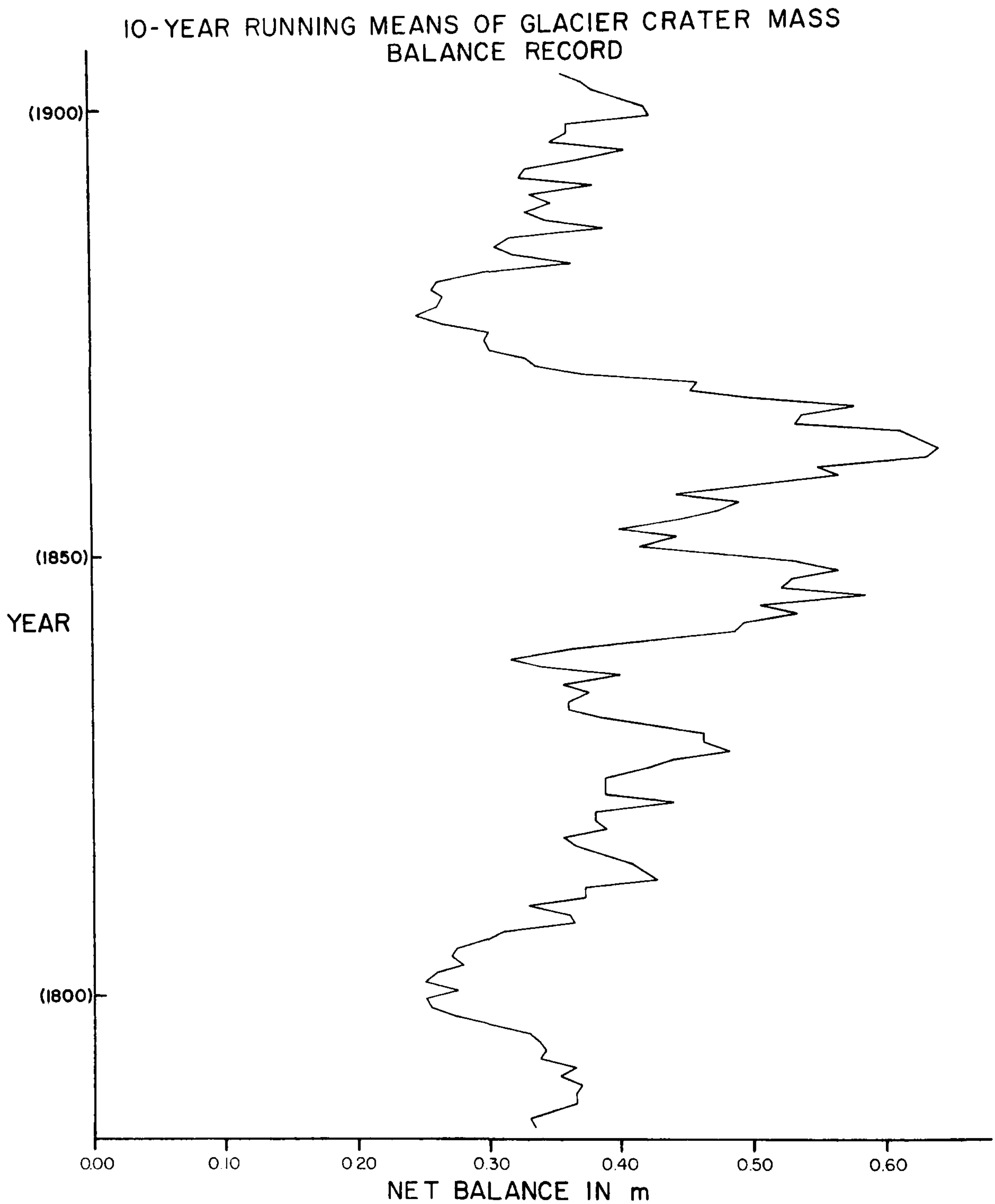

Figure 11. 10-year equal-weighted running means of crater mass balances.

Reliability of the Mass-Balance Data

Three types of uncertainties are present in the mass-balance data both from the glacier fissure and the glacier crater. These are (1) uncertainties in the identification and measurement of the annual layers, (2) uncertainties caused by missing years because of negative mass balance, and (3) uncertainties caused by glacier flow and post-depositional changes. The first two types chiefly affect the dating of layers, whereas the third type involves non-climatic effects introduced in the measured mass-balance records. There is also uncertainty in the absolute age of the ice exposed in the glacier crater, as cussed on pages 24 and 25.

Uncertainties in the Identification of the Annual Summer Surfaces

Uncertainties in the identification of the annual summer surfaces can arise from (i) a summer surface being missed, (ii) multiple dirt layers being formed in a single year, and (iii) problems in distinguishing between summer surfaces and layers formed by deposition of volcanic material either during an eruption or by subsequent seepage.

(i) The summer surfaces are very well marked by their dust content, and great care was taken during the stratigraphic studies to note all dust inclusions in the ice. It is considered very unlikely that any summer surfaces were missed during the stratigraphic studies, and the uncertainty from this source is taken as 0 years.

(ii) Two faint dirt layers close together may form in one summer under the very rare condition of long ablation periods, in early and late summer, separated by a period of heavy precipitation falling as snow at higher elevations. Two pairs of layers in the fissure record, separated by 0.01 and 0.05 m, have been tentatively identified as having formed in a single year, in 1942 and 1910. There is thus a possible maximum error in the ages of +1 year below 1942, and +2 below 1910. No such pairs have been identified in the crater record, and the error here is 0 years.

(iii) The volcanic material deposited during an eruption can cause uncertainties, firstly by being misidentified as summer dirt layers, secondly by masking the dirt layers, and thirdly by introducing particles by seepage into the layers below.

It is unlikely that a volcanic layer has been mistaken as a summer surface. The volcanic layers contain from 10 percent to nearly 100 percent pyroclastic material, and the largest particles usually exceed 1 mm in diameter whereas the summer surface layers usually contain less than 1 percent dirt particles of approximately 0.1 mm maximum diameter. The estimated maximum error from mistaken identification is 0 years in the fissure, and -1 year in the age of the lower layers in the crater.

Volcanic eruptions in the summer will mask the dirt layers. The season of the eruptions was therefore studied by searching for dispersed particles (which would indicate summer melt) in the ice immediately below the volcanic layers. This seasonal identification is uncertain for the thin layers, and it is impossible for the thick layers. There is one thick volcanic layer in the fissure, and two in the crater, and all these have arbitrarily been counted as annual layers. The estimated maximum error in the ages from the masking effect is +2, -3 years for the fissure, and +3, -5 years for the crater.

Both the fissure and the crater exhibit several sections (totalling about 5 m thickness for each) of finely-dispersed dirt particles. The origin of these is not established in all cases, but some were clearly formed in firn by seepage from volcanic deposits. The dispersed particles appear in similar concentrations to those of the summer surfaces, but they are much more irregularly distributed laterally. The two forms were distinguished by studying the stratigraphy in very wide sections. The estimated maximum error from this source in the age of the lower layers is ± 2 years for each record.

The cumulative estimated maximum error from all stratigraphic sources for the ages of the lowest layers is ± 5 years for the fissure, and -8, +5 years for the crater. An estimated probable error is ± 3 years for the fissure, and -5, +3 years for the crater.

Uncertainties in the measurement of the water content arise from the uncertainties in the measurement of the ice thickness and density of the layers. Of these the former are random and are considered negligible.

The density value of the ice exposed in the fissure section contains possible uncertainties because of the few measurements. But the uncertainties are unlikely to change the average water equivalent of the layers by more than 0.01 m, and they do not significantly affect the year-to-year variations.

A uniform density of 0.9 Mg m^{-3} has been ascribed to the ice exposed in the crater section. There can be no significant error in this figure.

Uncertainties Caused by Missing Years

Uncertainties caused by missing years due to zero or negative balance are the most important uncertainties in the crater record, and they also affect the fissure record. The probability that the annual balance should deviate by the amount of the mean, from the mean, can be found from the ratio of the mean to the standard deviation, provided the balances are normally distributed. For the fissure the mean is 0.47 m, with $\sigma = 0.27$ m. The ratio of these is 1.72. The probability of a negative deviation $> 1.72\sigma$ equals 4 percent, i.e. the frequency of missing years is 1 in 25. Similarly, the probability of missing years is 6.5 percent for the crater record, corresponding to a frequency of 1 in 16.

Three errors exist in the above argument. Firstly, introducing years of balance ≦ 0 reduces the mean in proportion to the number of added years, and it increases the standard deviation, thus increasing the likelihood of missing years. Secondly, the balances are positively skewed, with fewer but larger, deviations above the mean than with a normal distribution, corresponding to the positive skew distribution found in most yearly precipitation data. The positive skewness means that it is less likely than indicated by the above calculations that the balances will deviate by large negative amounts. Thirdly, the water equivalent of the layers has been reduced by vertical thinning due to ice flow (discussed below). Compensating for this thinning increases the ratio of mean to standard deviation, because the largest absolute corrections are on the layers with the most negative deviation from the mean. Exact calculation of the frequency of missing years is not possible, but a consideration of the combined effects of these three factors suggests that the frequency is less than indicated by the above calculations, being about 1 in 50 years for the fissure, and 1 in 30 years for the crater.

At present there are no absolutely known dates available for the sections, and the above figures cannot be tested. However, meteorological evidence, discussed below, suggests that for at least the past 20 years there have been no years of negative balance at the fissure. This confirms that the estimated number of missing years is reasonable. A further treatment of this question may be possible when radiometric dates are available.

Non-Climatic Changes in Balance

The non-climatic changes in balance are of three main types: (i) variations in the balance because layers now at different depths in the sections were deposited on different parts of the glaciers, (ii) changes caused by vertical thinning, and (iii) changes caused by refreezing of meltwater in the firn.

(i) The elevation of the area of origin of the layers increases with increasing layer depth. The net balance increases with elevation; thus the net balances in the section should increase from this effect. This increase in balance has been evaluated approximately from flow-line considerations, together with data on the variation of net balance with elevation obtained from glacier G 1 and, from less extensive data, from "Black" Glacier above the fissure. The balance differences between the lowest and highest layers of the section produced by this effect are 0.2 m for the fissure, and between 0.05 and 0.1 m for the crater. For both sections the increase in balance is approximately linear.

(ii) Various theoretical and empirical treatments of the vertical thinning due to ice flow have been proposed. The most widely used is that of Nye (1963), who assumed firstly that basal melting is negligible, and secondly that at any instant the vertical strain along a vertical line in the ice is uniform with depth. The first assumption is not valid for the two glaciers considered here. The Nye model, when corrected for basal melting, indicates that the thinning increases linearly from zero at the surface to between 50 and 60 percent at the base of the fissure section, and from nearly zero to about 50 percent at the base of the crater section.

Nye's second assumption has not been established by field studies, and models in which the vertical strain rate increases with depth have been used recently for cold-based ice sheets, by Dansgaard and Johnsen (1969), and by Philberth and Federer (1971). The vertical strain rate may also be non-uniform for the glaciers considered here. Any non-uniform increase in strain rate will most likely occur in the lower part of the ice, below the sections considered here. A rough estimate for the non-uniform case is that the strain increases approximately linearly for both sections to reach between 30 and 50 percent at the lowest parts.

(iii) Refreezing of meltwater occurs in spring until the snow and firn in the accumulation area is isothermal at 0 °C. Observations at G 1 and climatic data indicate that 0.05 to 0.10 m is normally refrozen in the firn. Each layer passes through a cycle, in losing mass to the layers below during the first summer after deposition, and then gaining mass by percolation from overlying layers over the following few years until it is below the level of the winter cold wave. The mass change after the layer has gone through this cycle of losing and gaining mass can be expected to be less than 0.05 m. This is ignored for both sections, except for the upper few layers of the fissure section, which have not passed through the complete cycle, and which require minor additions to become comparable with the layers below.

No corrections have been made in the data presented in Figs. 8-11 for the opposing linear trends in measured mass balance, caused by changing the elevation of the area of origin of the layers and by vertical strain. The application of these corrections and the combination of the two records into a single uniform record is discussed in the following section.

Combination of the Fissure and Crater Records into a Homogeneous Mass-Balance Record

Two steps are necessary before the mass-balance records for the crater and the fissure can be combined into a single record reflecting mass-balance conditions on the glacier surface. First, the non-climatic changes must be removed from the records. Second, the crater record must be tied in age to the fissure record.

Removal of Non-Climatic Effects

The changes in mass balance caused by vertical strain and by the changing elevation of the area of origin of the layers can be considered to increase linearly with depth from zero at the surface (see above), and can then be corrected for as follows:

Let the amount of vertical strain experienced by the lowest layer in the section be s, and the difference in annual mass balance between the areas of origin of the highest and lowest layers in the section be Δb. We assume for the moment that the climate is constant, with the annual balance at the area of origin of the highest layers of the section equal to b_a. This is called the surface balance. If there were no non-climatic effects, the surface balance would equal the measured balance. With the non-climatic effects, the measured average balance, $\bar{b}_m$, becomes

$$\bar{b}_m = (b_a + (b_a + \Delta b)(1-s))/2 \qquad (1)$$

Limiting values for $\bar{b}_a$, the mean true surface balance of each section, can now be calculated using the estimated limits for s and Δb given earlier. For the fissure, the measured average balance is 0.473 m, s is between 30 percent and 55 percent and Δb is 0.2 m. Substituting in (1) indicates that $\bar{b}_a$ should be between 0.590 m (maximum strain) and 0.474 m (minimum strain). For the crater, s is between 30 percent and 50 percent, Δb is between 0.05 and 0.10 m, and the measured average balance is 0.390 m. Here $\bar{b}_a$ should be between 0.504 m (maximum strain, minimum Δb), and 0.418 m (minimum strain, maximum Δb).

It is clear that the non-climatic effects have acted to reduce the surface mass balances as measured in both sections. However, the uncertainties in the strain model make it impossible to place closer limits than indicated on the true means of the surface balance. As no definitive theoretical treatment of the vertical strain problem is presently available, it seems best not to choose between the two models, but to use the average of the results from the two models, as the basis for adjusting the measured balances (always keeping in mind that the real strain may be different). This indicates that the true average annual surface balance for the fissure should be 0.532 m, and for the crater 0.461 m. That the mean of the fissure is greater than that of the crater is expected, as the ice now exposed in the fissure originated at 75-100 m higher elevation. For example, if the net balance curve for the fissure and crater area varied with elevation in the same manner as on glacier G 1 (Figs. 20-22), a 75-m elevation difference would correspond to a net balance difference of 0.15-0.20 m.

So far the climate has been assumed constant, which is incorrect. Non-linear climatic variations which give rise to non-linear mass-balance variations do not invalidate the previous arguments, and these variations are preserved after the measured balances have been corrected by linear functions to give the real means determined above. A trend in climate giving linear change in mass balance may, on the other hand, be masked by the corrections. Minimum variance fit lines show a decrease in annual balance with depth for both records, amounting to

0.00137 m a^{-1} for the fissure and 0.000329 m a^{-1} for the crater. When these trends are added to the measured balances, the mean for the fissure becomes 0.519 m, and for the crater 0.412 m.

The linear trend in mass balance with time for the fissure can be explained completely by the non-climatic effects, as it falls within the limits of the assumed strain models, requiring a strain of 40.6 percent on the lowest layer. In other words, no conclusion can be drawn regarding linear change in mass balance from 1905 to 1971, except that if there has been a linear change it has probably been a decrease in annual mass balance toward the present, as the trend in the records corresponds to a smaller-than-average strain model.

The situation is different for the crater section. Here the decrease in balance with depth is less than expected with the minimum strain model, indicating that there is an increase in balance with depth, caused by more positive surface mass balances when the snow forming the lower parts of the section was deposited. However, the differences between the trend of measured mass balances and the trend calculated from the lowest strain model are not great, and with the uncertainties present, it can only be tentatively concluded that a linear change of decreasing surface net mass balance has taken place from 1780 to 1910.

The two records may now be normalized by adding a linear trend to each, to increase the mean balances so that they equal the mean surface balances for the average results of the strain models, and then the mean is subtracted. The minor corrections for refreezing of meltwater at the fissure are also included. The equations for the linear corrections are, in m: $b_a = b_m + 0.00178t - 0.532$ for the fissure, and

$$b_a = b_m + 0.00106t - 0.461 \text{ for the crater,}$$

where t is the number of years measured from the surface.

To be quite precise, the linear increase caused by strain should not be proportional to age but to the depth and thickness of the layer (thicker layers experience larger absolute values of strain). However, to make the corrections in this manner is complicated, and the differences between the resulting corrections and those calculated by the above equations are trivial compared with the uncertainties in the corrections. Furthermore, these differences are removed by smoothing and averaging of the records, and the records are used in these forms only to evaluate past climatic changes.

Correlating the Ages of the Crater and Fissure Records

The crater section does not extend to the present time, and the estimate of the age of the top of the section is based on six lines of evidence:

(i) Flow and mass-balance considerations suggest that the top of the crater section should be between 50 and 100 years old (Fig. 5).

(ii) The mass-balance variations for the top 9 years of the crater section are significantly correlated ($r = +0.76$, $P < 0.02$) with the lowest 9 years of the fissure section. There is no other overlap of the records which gives a significant correction.

(iii) With the 9-year overlap the main eruption layers in the two records coincide in time. It should be noted in connection with (ii) and (iii) that the stratigraphic work in the fissure and the crater was completely independent.

(iv) Mass-balance variations for 9 additional years below the fissure wall section have been obtained by analysis of an 8.2-m-long core drilled with an Acker Pack Sack power drill at the base of the fissure in 1971. Adding these to the 9 years from the fissure stratigraphy gives an 18-year overlap with the crater section, which also is significantly correlated ($r = + 0.76$, $P < 0.001$). The core was taken about 30 m laterally from the area of the fissure wall stratigraphy and is firmly tied to this stratigraphy by a 3-m overlap which included the unmistakable eruptions between 1906 and 1909. The core stratigraphy is shown in Fig. 12. The mass-balance curves for the fissure wall, the fissure core and the crater, and the eruption events in each section, are shown in Fig. 13. It should be noted that the fissure core was analyzed in the laboratory after the overlap was suspected and this may unconsciously have affected the interpretation. The interpretation of the core is in any case much less certain than for the other two sections, chiefly because (a) the core has a narrow diameter of 0.025 m, and (b) parts of the core may have been contaminated by dirt particles during the drilling.

The first difficulty is particularly a problem at about 3 m depth in the core section; the small section exposed made it impossible to distinguish the eruption layers between 1906 and 1909. Thus the core here was assumed to have three annual layers in accordance with the other two sections (Figs. 12 and 13). The interpretation in these other two sections for those eruption years is incidentally not completely certain either, because of the uncertainties in distinguishing summer surfaces from eruption layers. Thus there is some subjectivity in all three records at this point which may make the overlap look better than is really the case.

The second difficulty, contamination of the core, is particularly the case at the top of each of the six sections that make up the 8.2 m section (Fig. 12). Each time the drill was replaced in the hole some dirt particles would tend to enter with it which would then contaminate the first few centimeters of the core. Any dirt found there would thus be ascribed to contamination and it is of course possible that a real summer surface may have been missed in this manner.

(v) If the above overlap is correct, then the age of the second largest eruption recorded in the crater section is stratigraphically dated to within a few years of 1842, the date of the eruption observed by Smyley.

STRATIGRAPHY OF CORE FROM BASE OF FISSURE

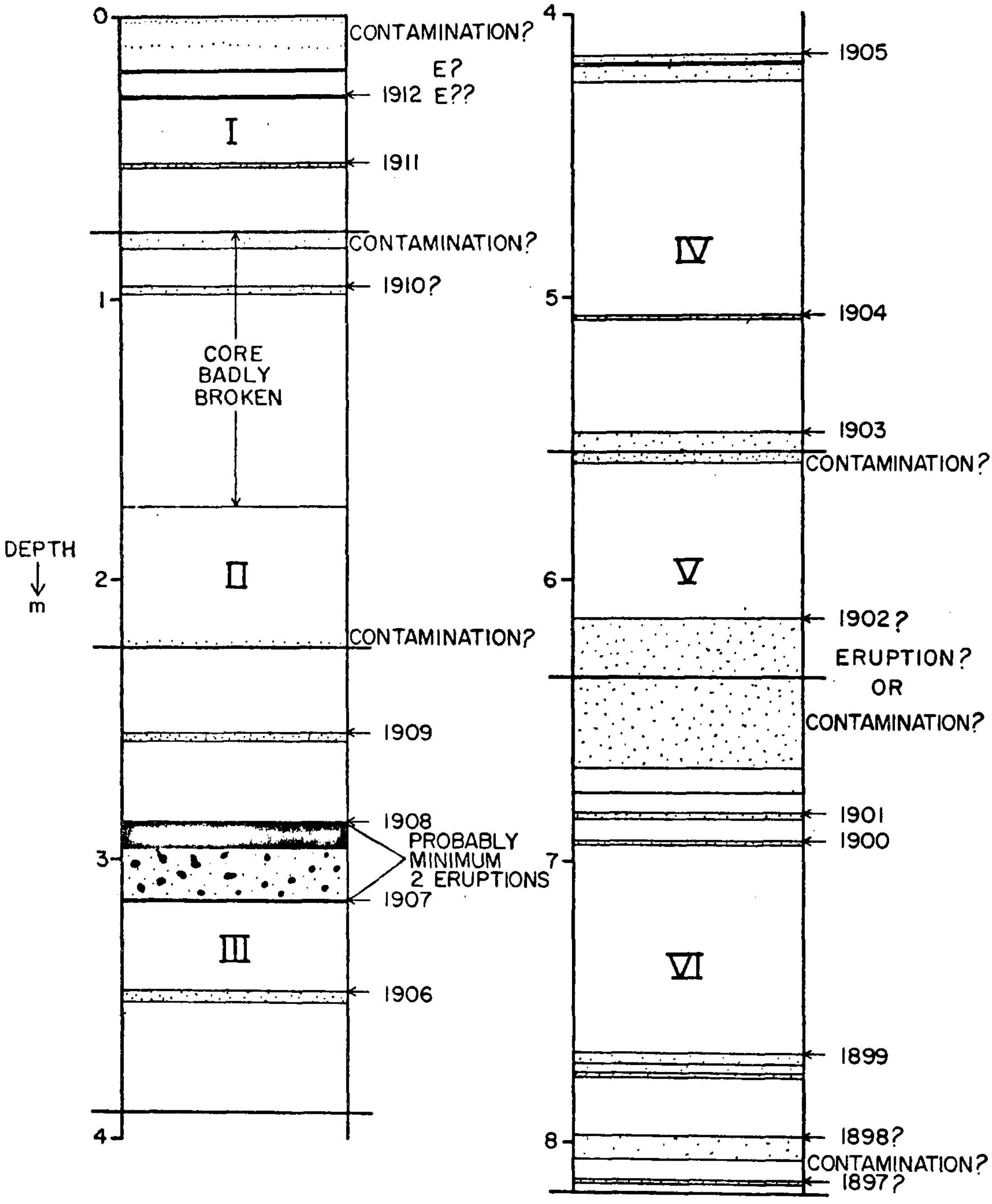

Figure 12. Stratigraphy of core from base of fissure. Individual core sections are marked by roman numerals and are separated by horizontal lines extending outside the core.

NET MASS BALANCE VARIATIONS FOR THE PERIOD OF OVERLAP BETWEEN THE FISSURE AND THE CRATER

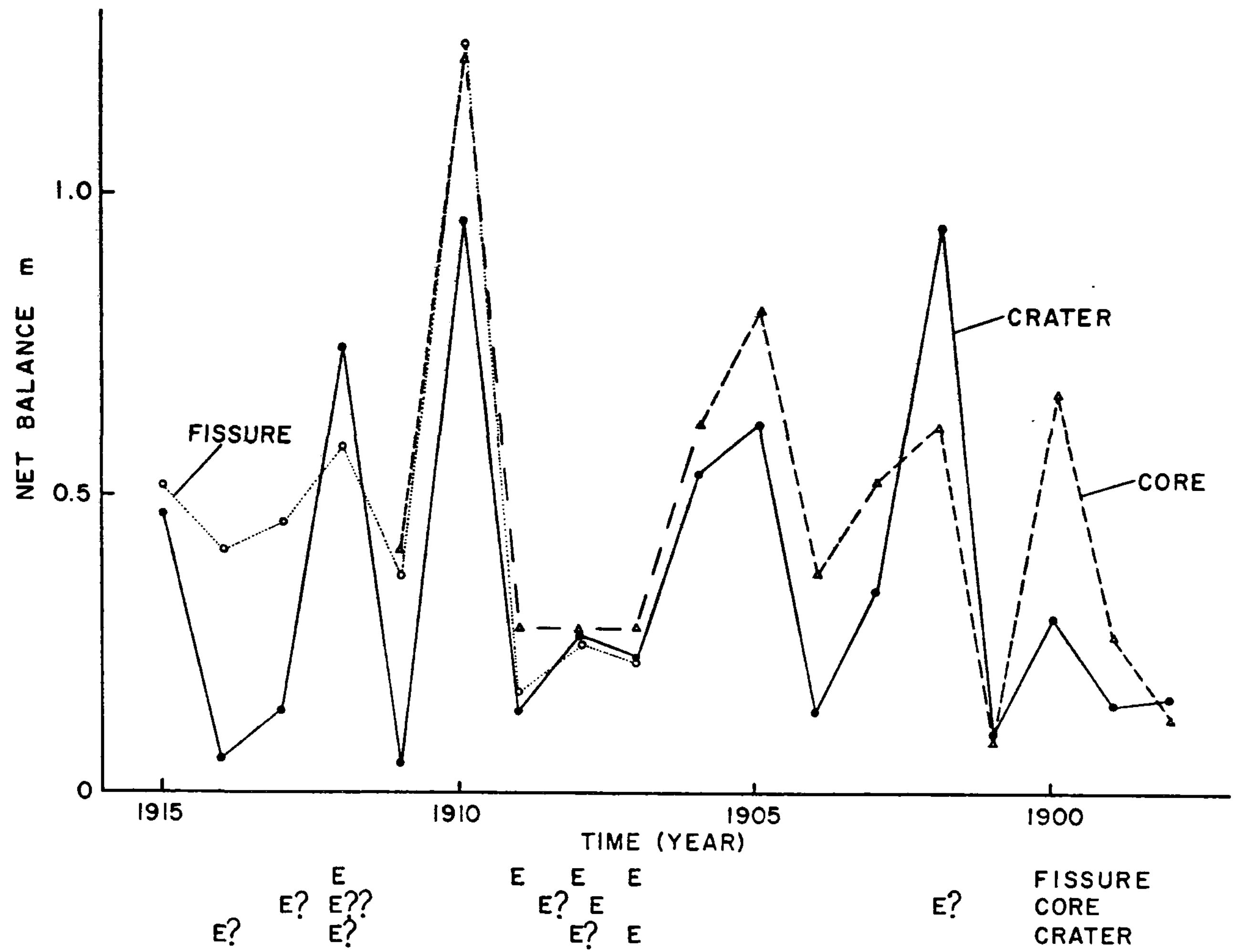

Figure 13. Mass-balance variations and recorded eruptions at fissure and crater for period of overlap. Long dashes show uncertainty in the core analysis.

(vi) The mean net balance for the top 18 years of the crater section is 0.21 m smaller than the mean for the combined lowest 18 years of the fissure section. This difference is very close to the difference of 0.15 - 0.20 m that could be expected from the elevation difference between the sections (p. 23), which supports the contention that the two 18-year intervals coincide in time.

The normalized records from the fissure and crater are now combined to give the record shown in Fig. 14. The values for the individual years are given in Appendix B. For the nine-year overlap the mean of the two records has been used. As the means of each record (0.532 m for the fissure, 0.461 m for the crater) were subtracted when the records were normalized the combined record is shown to vary around a mean of 0.

The 5- and 10-year running means of the combined record calculated with binomial smoothing are shown in Figs. 15 and 16, respectively. Figure 17 shows the 10-year equal-weighted running means. This record is included to facilitate comparison with records elsewhere, which are commonly given in this form.

The estimated maximum uncertainty in the ages of the combined record is found by adding the estimated maximum uncertainties for each section (given earlier). This gives a maximum uncertainty of -11, +13 years on the age of the lowest layer in the combined record. The estimated probable error on the oldest layer is -7, +5 years (taking the error as the square root of the sum of the squared errors). No error is ascribed to the overlap, because if it is correct there is no error introduced. If it is not correct an unknown and constant additional error is introduced in the ages of the crater record. A major objective of the radiometric dating of the ice in the crater section is to test this overlap.

A further error in the estimated ages of the various layers is caused by the possibility of missing years (in which the balance is zero or negative). As estimated earlier, these number 1 in 50 years for the fissure, and 1 in 30 years for the crater. These missing years are <u>not</u> introduced in the record, and the ages indicated for the layers are therefore probably 1 year too low for the lower layers of the fissure record and should further be increased by 1 year for every 30 years below 1910.

The lowest layer then becomes about 6 years older than indicated in the figures and in appendix B, that is, the record extends to year A.D. 1776-77, rather than 1782-83. The number of missing years is approximate, of course.

One further test of the frequency of missing years can be made, however, by comparing the ratio of the mean to the standard deviation, for the combined sections in the manner done earlier for the separate sections. The complete record has a mean of 0.485 m, with $\sigma = 0.258$ m. That the balance should be ≤ 0 means a deviation from the mean of 1.88σ, which for a normal distribution has a probability of 2.9 percent,

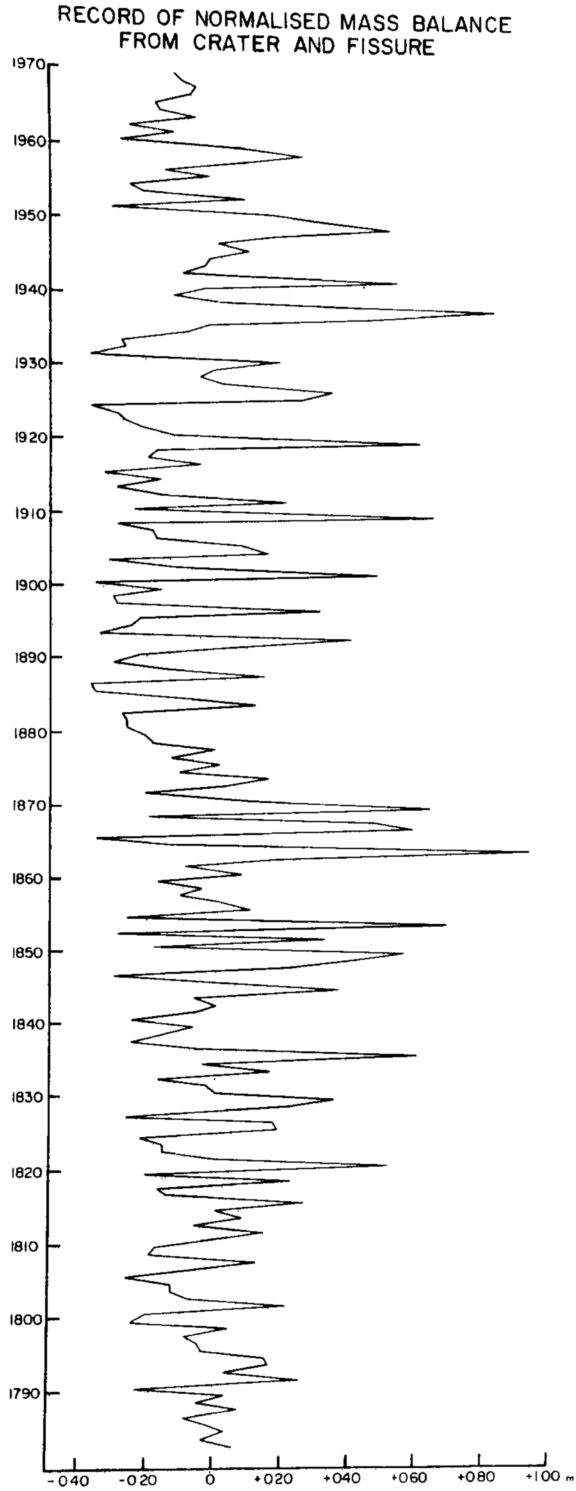

Figure 14. Record of normalized mass balance from crater and fissure.

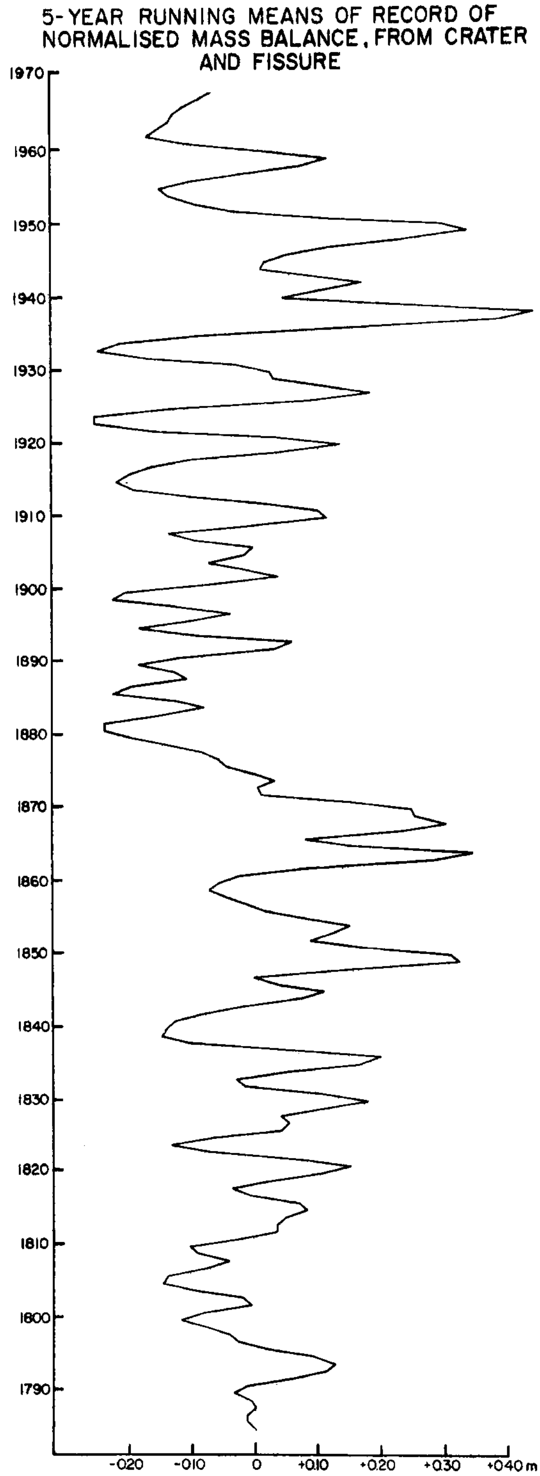

Figure 15. 5-year running means of record of normalized mass balances. The balance values are smoothed by the binomial function $(b_{n-2} + 4b_{n-1} + 6b_n + 4b_{n+1} + b_{n+2})/16$.

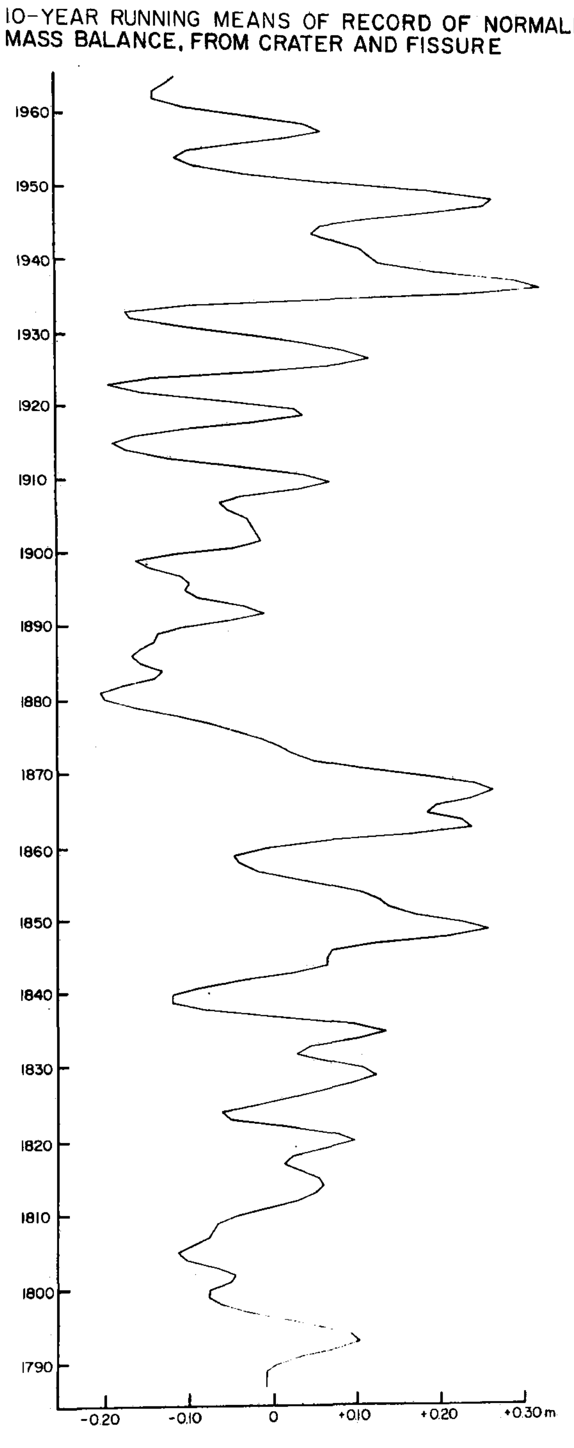

Figure 16. 10-year running means of record of normalized mass balances. The balance values are smoothed by the binomial function $(b_{n-5} + 9b_{n-4} + 36b_{n-3} + 84b_{n-2} + 126b_{n-1} + 126b_n + 84b_{n+1} + 36b_{n+2} + 9b_{n+3} + b_{n+4})/512$, and are plotted at n + 0.5 year.

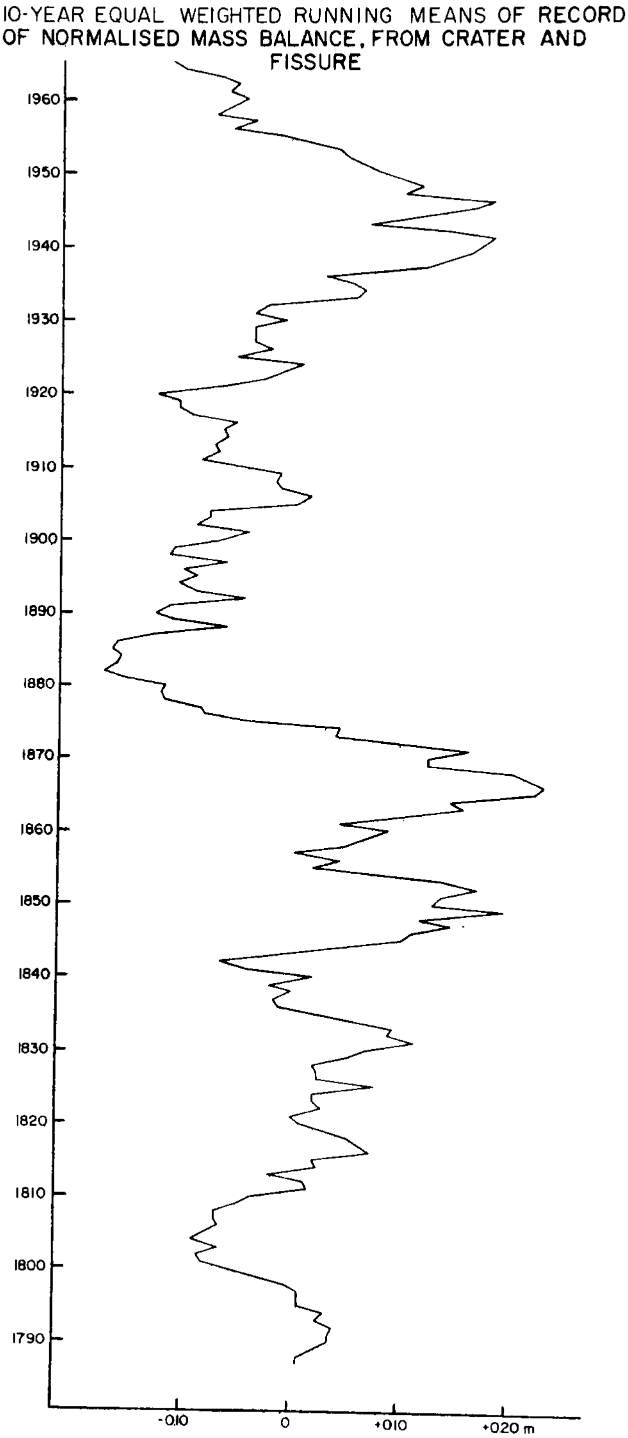

Figure 17. 10-year equal-weighted running means of record of normalized mass balances.

or 1 in 34 years. The uncertainties in this procedure discussed earlier make this only an estimate of the order of magnitude of missing years, but it shows that the order of magnitude given above is reasonable.

It is clear from the preceding sections that, in addition to the possible stratigraphic inaccuracy of age of the crater section, two errors may have been introduced into the combined record: (i) a single-step function at the point of overlap, and (ii) linear trends of limited magnitude in both parts of the record. Obviously, no conclusions about mass balance trends should be drawn which can be explained by (i) or (ii). With this in mind, the single record can be used as a record of surface mass balance variations from 1780 to the present. However, before it is used as an indicator of variations in local climate it is necessary to consider whether the mass balance record could have been affected by former volcanic eruptions.

EFFECTS OF VOLCANIC ERUPTIONS ON MASS BALANCES

The extent to which the volcanic eruptions affect the mass balances of the glaciers has been studied in two ways: (1) by investigating the effects of the recent volcanic eruptions on the glaciers of the island, and in particular at G 1, and (2) by comparing the measured mass balances with those at Rotch Ice Dome on Livingston Island, 30 km to the north, which has not experienced recent volcanic activity.

Effect of Recent Volcanic Eruptions on the Glaciers of Deception Island

The main visible effect of the three recent eruptions has been to deposit volcanic ash over most of the glaciers. The effect of this ash differs in the accumulation and ablation areas of the glaciers. In the accumulation areas the ash is buried during the subsequent winter and after burial generally ceases to affect the heat and mass balances. Only near the equilibrium line, where the snow cover is thin by late summer, may the ash result in increased absorption of radiation and thus increased ablation during the following year. On glacier G 1, where the problem was studied in detail, it was found that the effect of the ash in the accumulation area had become negligible one year after the eruption.

In the ablation area the ash is washed downslope by meltwater and is eventually deposited at the front of the glacier. The rate at which the ash is removed depends mainly upon the quantity deposited and the local slope. A relatively small amount of ash was deposited on glacier G 1 by the 1967 and 1969 eruptions, and much of it was washed off after 2 or 3 summers. No ash was deposited on G 1 by the 1970 eruption. Other glaciers on the island still show a complete cover of ash on their ablation areas. Where the ash cover is thin it has increased the ablation rate, but in most instances the ash cover is so thick that it effectively insulates the underlying ice (see e.g. Østrem, 1959).

All of the ice examined in the glacier sections originated high in the accumulation area of the glaciers, where any ash is buried within one year. The effect of this ash is therefore short-lived, and the effect is confined to the relatively small number of years within each section containing ash. For these years there is no correlation between ash thickness and annual balances, and it is concluded that the ash has had no significant effect on the mass balance record.

The subglacial volcanic eruptions in 1969 and 1970 had large local effects, both by destroying large sections of the glaciers and subsequently by increasing the ablation rates (Orheim, unpublished). However, the orderly arrangement of the layers exposed in the fissure and crater sections definitely excludes the possibility that these layers had originated from or passed through areas of the glaciers affected by subglacial eruptions.

Finally, it must be considered whether the volcanic activity can change the weather at Deception Island. It is possible that the fumarolic activity causes a slight increase in the air temperature, and perhaps causes increased cloudiness. However, earlier descriptions and measurements of fumarolic activity (Kendall, 1831; Wilkes, 1845; Holtedahl, 1929; Olsacher, 1956; Hawkes, 1961) are very similar. This indicates that the fumarolic activity has been constant throughout historic time, so that if it has affected the weather and climate, it has probably been a constant effect and can be ignored in studies of the climatic variations. It is clear that volcanic eruptions do affect the weather at the time of eruption (Limbert, 1969), but it seems that these changes in weather do not persist more than a few days after the eruption terminates. The three recent eruptions have all been explosive and short-lived with a duration of a few days, and evidence from the glacier sections and from surface geology shows that all or nearly all the eruptions during the past 200 years have also been explosive and hence probably also of short duration. Twenty-three probable eruptions are recorded in the measured ice sections for this period, and while this is perhaps only half the number of actual eruptions it is clear that the effect of these eruptions on the climate of the island has been negligible.

Comparison Between Mass Balances at Deception Island and at Rotch Ice Dome, Livingston Island

The Rotch Ice Dome study was started in the 1970-1971 summer, and the data for comparison with Deception Island are limited. It seems that the winter balances are about the same at equal elevations in the two places, whereas the Deception Island glaciers show much larger negative summer balances. This difference is caused by the lower albedos on the Deception Island glaciers, resulting from deposits of large amounts of windblown dust, which causes increased absorption of solar radiation and hence increased ablation rates (Orheim, 1971). The amounts of dust deposited on the glaciers in recent years were probably larger than normal because of the eruptions, but there must always have been considerable quantities of dust deposited, as fine-size particles are always available in summer from the half of the island that is covered by loose volcanic material. The amount of dust deposited has varied from year to year, as is shown in the ice stratigraphy, but this will have been because of climatic effects, chiefly varying times for the winter snow to melt off the ice-free ground, and will not have caused the climate effects.

In conclusion, there are no significant effects from the volcanic eruptions on the mass-balance records, and this record is then a true measure of the mass-balance variations caused by climatic variations.

The relationship between these variations must now be established. To do this it is first necessary to understand the present mass and heat balance conditions of the glaciers on the island, and to this purpose a detailed study was carried out on glacier G 1, situated in the southwest part of the island (Fig. 1).

PRESENT MASS AND HEAT BALANCES OF GLACIER G 1

Glacier G 1 is a small (0.42 km^2) valley glacier (Fig. 18) of 0.9 km total length and with a mean slope of 18°. The glacier surface is in four steps, of which the lower two show slope differences of about 30° between the riser and the tread (Fig. 19). The glacier is situated about 10 km from the three recent eruptions and was not significantly affected by these eruptions (Orheim, in press, a). The mass and heat balance results obtained on G 1 are therefore representative of the general non-volcanic conditions on the island.

Mass Balance of Glacier G 1 for Balance Years 1968-1969 to 1970-1971

The results presented, and the symbols and terms used, are in accordance with the stratigraphic system (International Association of Scientific Hydrology, 1970). The mass-balance measurements were carried out according to common practices (see for example Østrem and Stanley, 1969), and only a few facts and some special problems are therefore mentioned.

Between 42 and 45 mass-balance stakes were used during the three years. These stakes were distributed approximately evenly over the glacier. Depths of snow to the previous summer's surface were measured at 40 points in 1969 and at 300 to 400 points in the following two summers, each point value generally being based on 2 to 3 measurements. Each stake represents about 10,000 m^2 of the glacier surface and for the past two summers each snow depth sounding point has represented about 1,000 m^2.

The basic approach to the mass-balance measurements has been to include as much of the mass lost and gained as can be obtained, even though it is realized that some of the figures are incomplete. Thus, for example, all observed summer accumulation is included in the following balance values but because the field seasons have been short these amounts probably represent no more than one-half of the total summer accumulation.

The summer ablation before or after each field season presents a particular problem. In 1968-1969, studies on the glacier started on 13 January, while the measurements were started one month earlier in the following two seasons. For the 1968-1969 balance year, only the net balance could be obtained, because an unknown amount of ablation of winter snow had occurred prior to the first measurements. Small amounts of ablation had also occurred in the lower parts of the glacier prior to arrival in the following two years, but runoff had not started from the upper parts, since the snow temperatures there were still negative. The early summer ablation for each of these two years has been computed by drawing an ablation curve from the highest point with runoff on the glacier, the slope of the curve being parallel to the

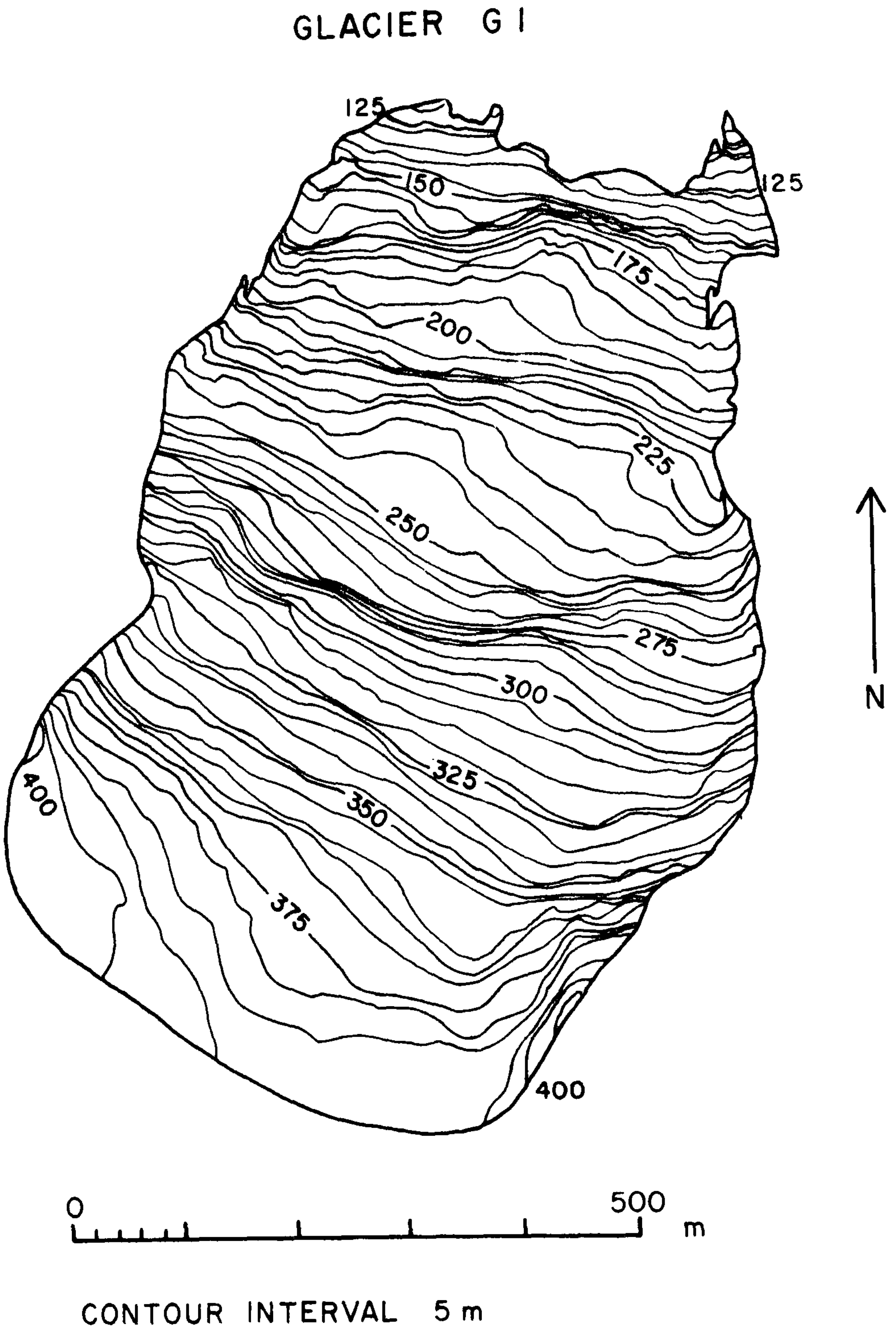

Figure 18. Glacier G 1, based on map plotted at a scale of 1 : 6,000 by H. H. Brecher at The Ohio State University from aerial photographs taken in 1956 by Hunting Aerosurveys, Ltd., England.

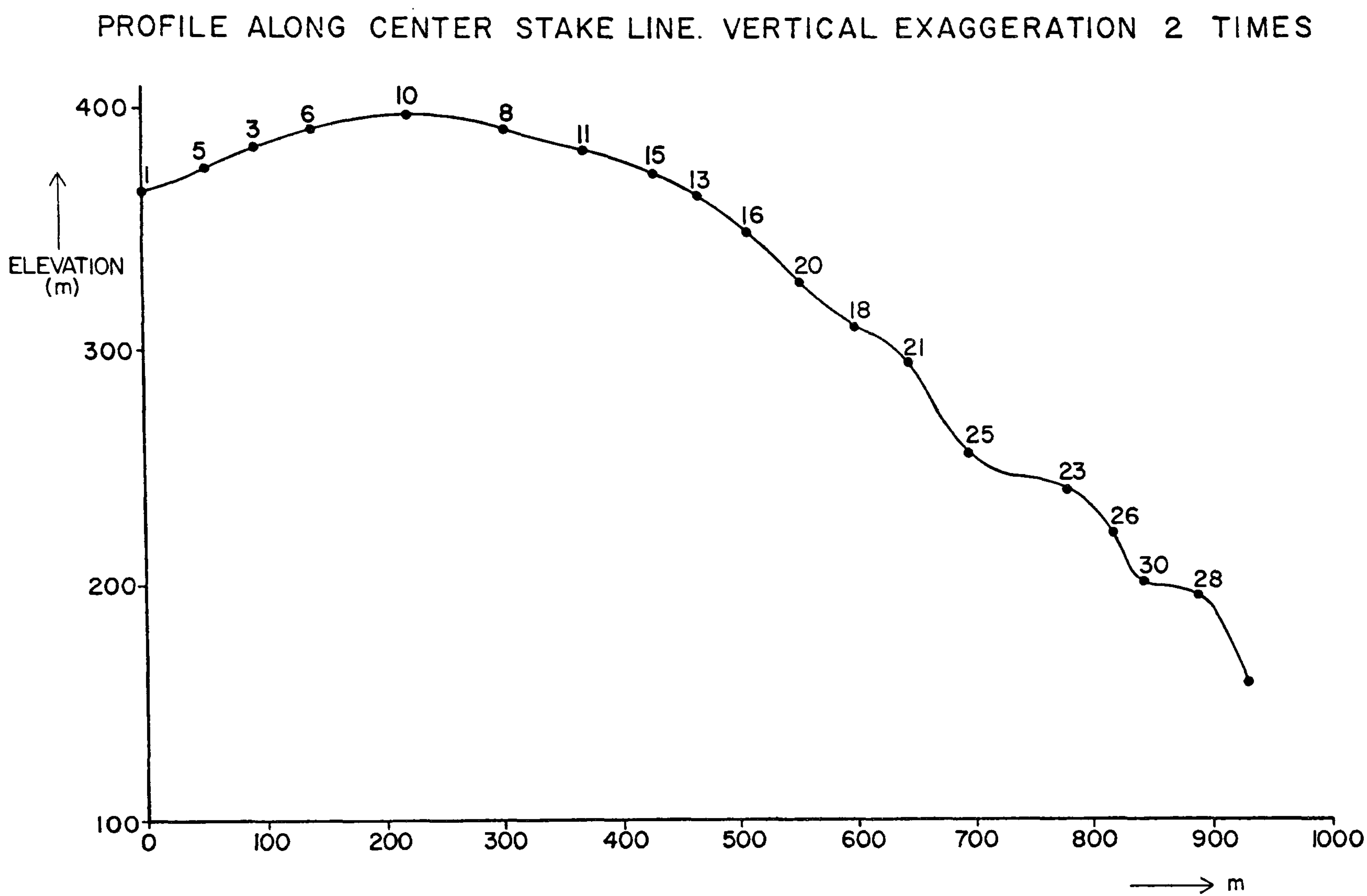

Figure 19. Profile along center line of glacier G 1, based on surveyed elevations.

ablation curve over the same surfaces determined from measurements later in the season.

The summer season also extended past the end of the field season in 1969, 1970, and 1971. The late summer ablation for each year was determined in the following season by measuring the lowering of the summer surface at the stakes, before the winter snow had melted. In the ablation area this is done by snow depth soundings, in the accumulation area by digging down to the summer surface.

The mass-balance values described in Figs. 20 to 25 and Table 1 include the summer accumulation and the early and late summer ablation. These have been added to the balance values determined for each 25-m elevation interval from maps of winter and summer balances. Practically all the early summer ablation is of winter snow and both this and the summer accumulation are quantities which affect the summer and winter balances by equal amounts, without changing the net balance. The late summer ablation is a net mass loss from the glacier and reduces the summer and net balances, while the winter balance remains unchanged. The complete mass-balance values for each 25-m elevation interval are given in Appendix C.

The errors indicated in Table 1 are estimated standard errors and result mainly from uncertainties in the early and late summer ablation, discussed above. The other principal uncertainties arise from (i) how well the stakes, soundings, and density measurements represent the true conditions on the glacier, and (ii) difficulties in defining the glacier boundary (for the areal values only).

The elevations of each of the steps on G 1 vary across the glacier. Thus parts of both the treads and the risers of the same step may fall within a particular 25-m interval used for computing the balance values. This tends to mask the effect of the topography in the balance curves presented in Figs. 20 to 25. In reality, the variations in balance are very large along lines transverse to the steps. Typically, on the lowest step of the glacier, shown in Fig. 19, the annual net balance is 2 to 3 m less on the riser of the step than on the tread. The surface ice velocity here is about 10 m a^{-1}. The balance variation across the step is sufficient to compensate for the forward flow of the ice, making the step stay fixed in space, from this effect alone.

The average gradients with respect to elevation of the summer, winter, and net balance curves are 6, 1 and 7 mm m^{-1} respectively. These gradients are defined as the slopes of the straight lines that best approximate the balance curves (minimum variance fit), and they characterize the glacier's condition.

The average gradient of the net balance curve is generally a better parameter for characterizing the activity of a glacier than is Shumskii's (1946) "energy of glacierization," which is the same as Meier's (1961) "activity index." These are defined as the slope of the

Table 1. Total and mean balances for glacier G 1, 1968-1969 to 1970-1971.

Period	Area($10^3 m^2$)	$B_w(10^3 m^3)$	$\bar{b}_w$(m)	$B_s(10^3 m^3)$	$\bar{b}_s$(m)	$B_n(10^3 m^3)$	$\bar{b}_n$(m)
1968-1969	418					- 4	-0.01±0.15
1969-1970	418	+293	+0.70±0.15	-420	-1.00±0.15	-127	-0.30±0.10
1970-1971	418	+179	+0.43±0.15	-415	-0.99±0.20	-236	-0.56±0.15

$\bar{b}_w$, $\bar{b}_s$, and $\bar{b}_n$ represent the areal mean values of winter, summer and net balances.
For other symbols see Figure 24.

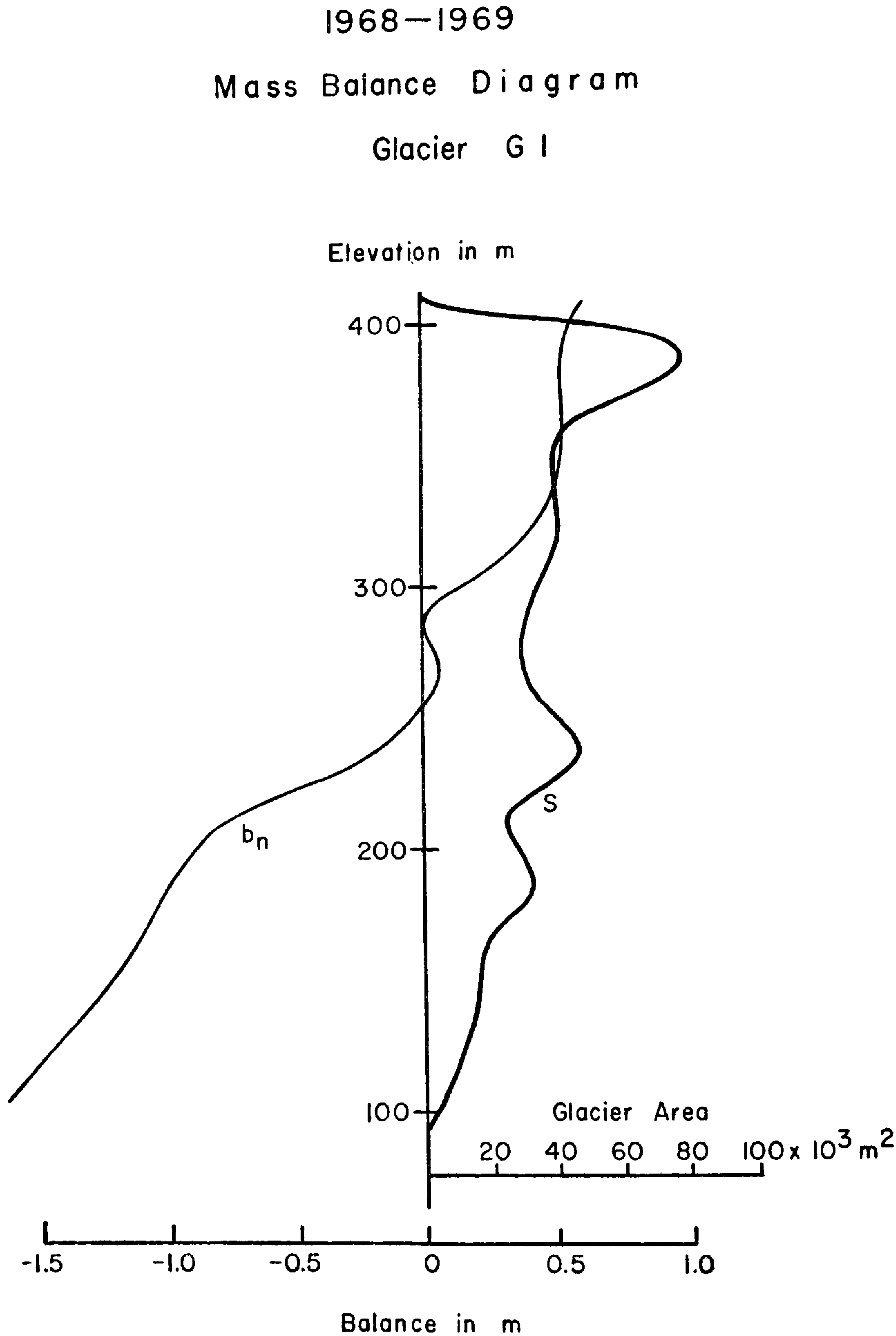

Figure 20. Mass balance diagram for glacier G 1 for 1968-1969. For symbols see Figure 21.

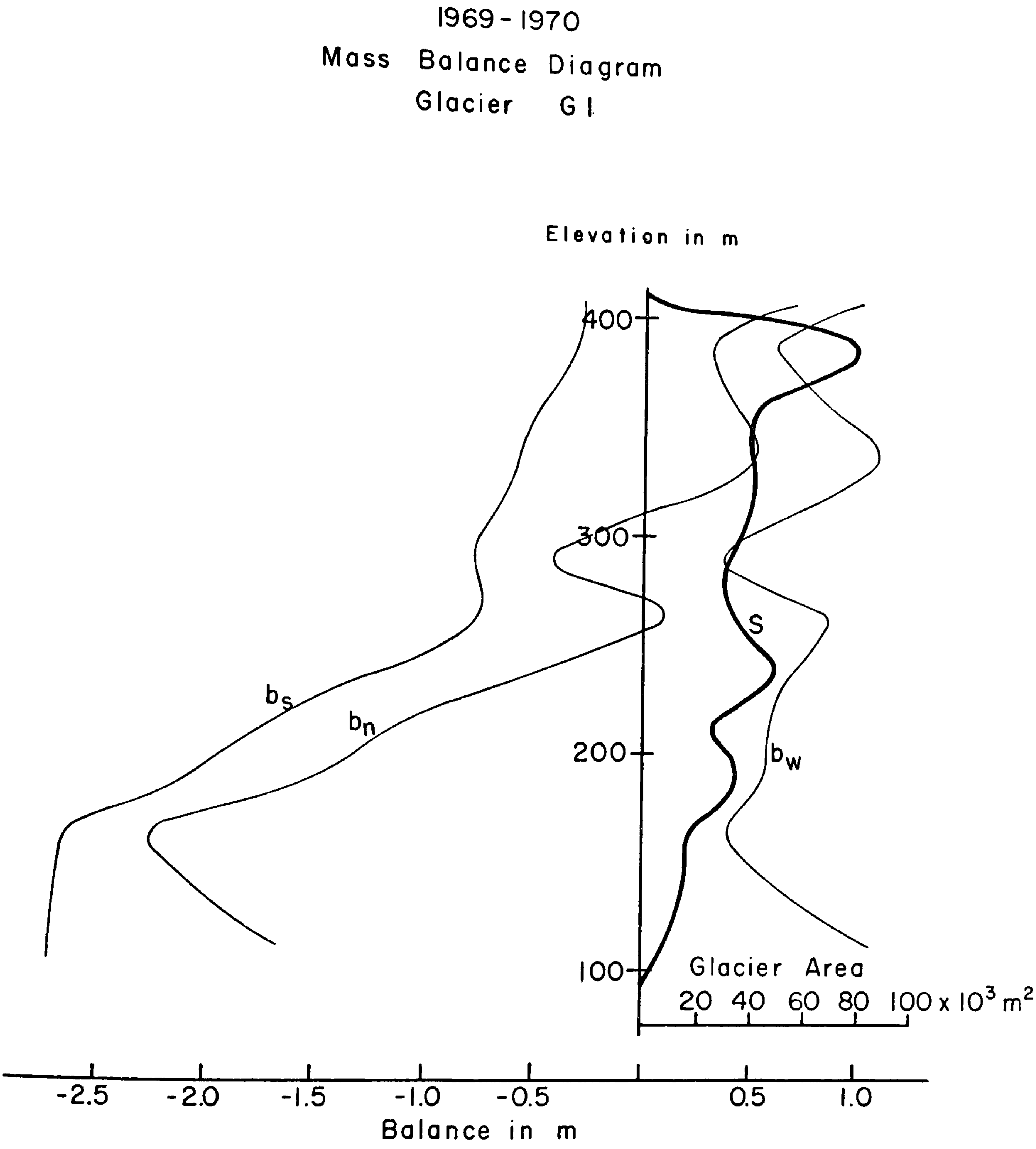

Figure 21. Mass balance diagram for glacier G 1 for 1969-1970. b_s = summer balance, b_n = net balance, b_w = winter balance, and S = glacier area.

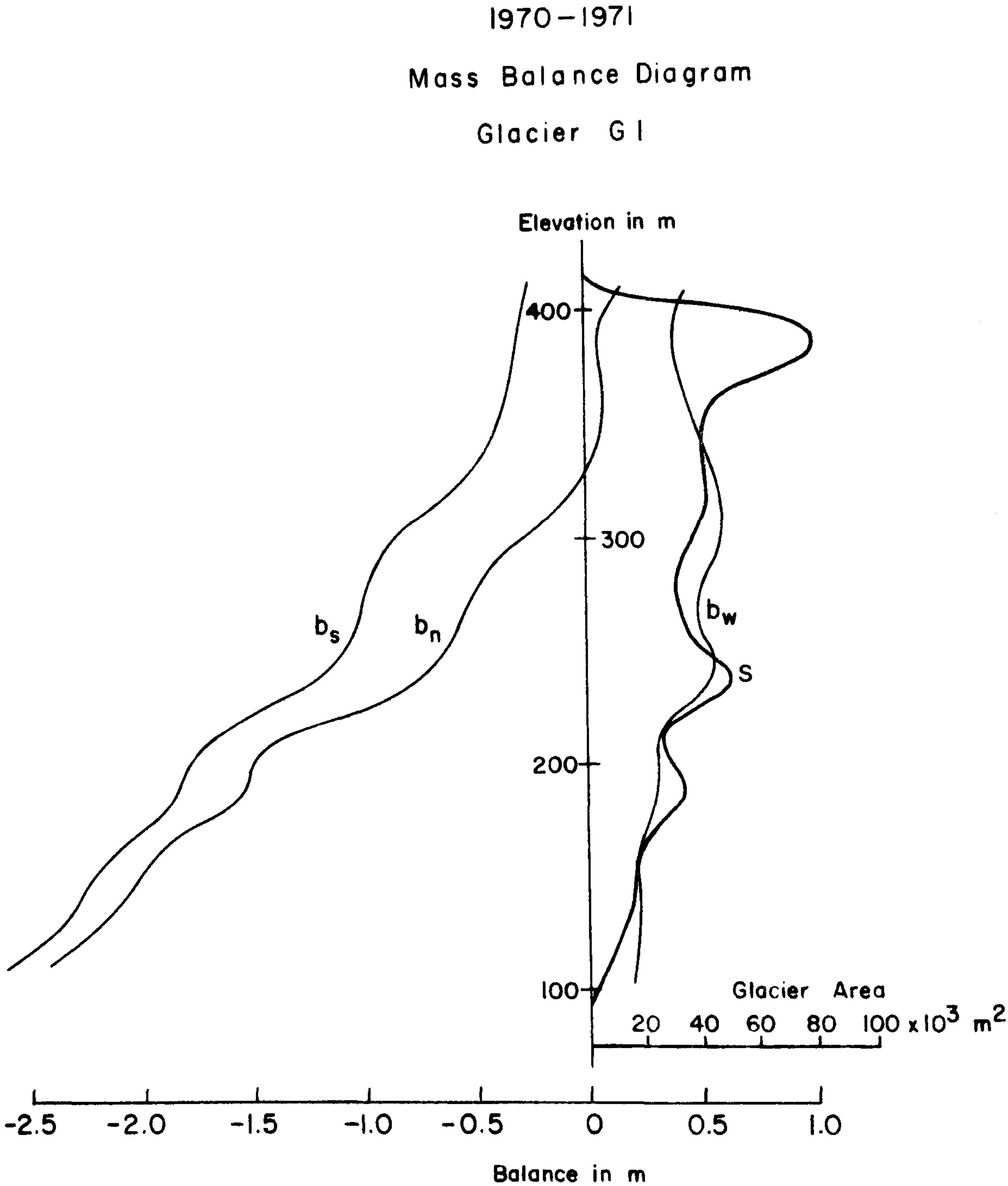

Figure 22. Mass balance diagram for glacier G 1 for 1970-1971. For symbols see Figure 21.

1968-1969

Variation of Balance With Elevation at Glacier G I

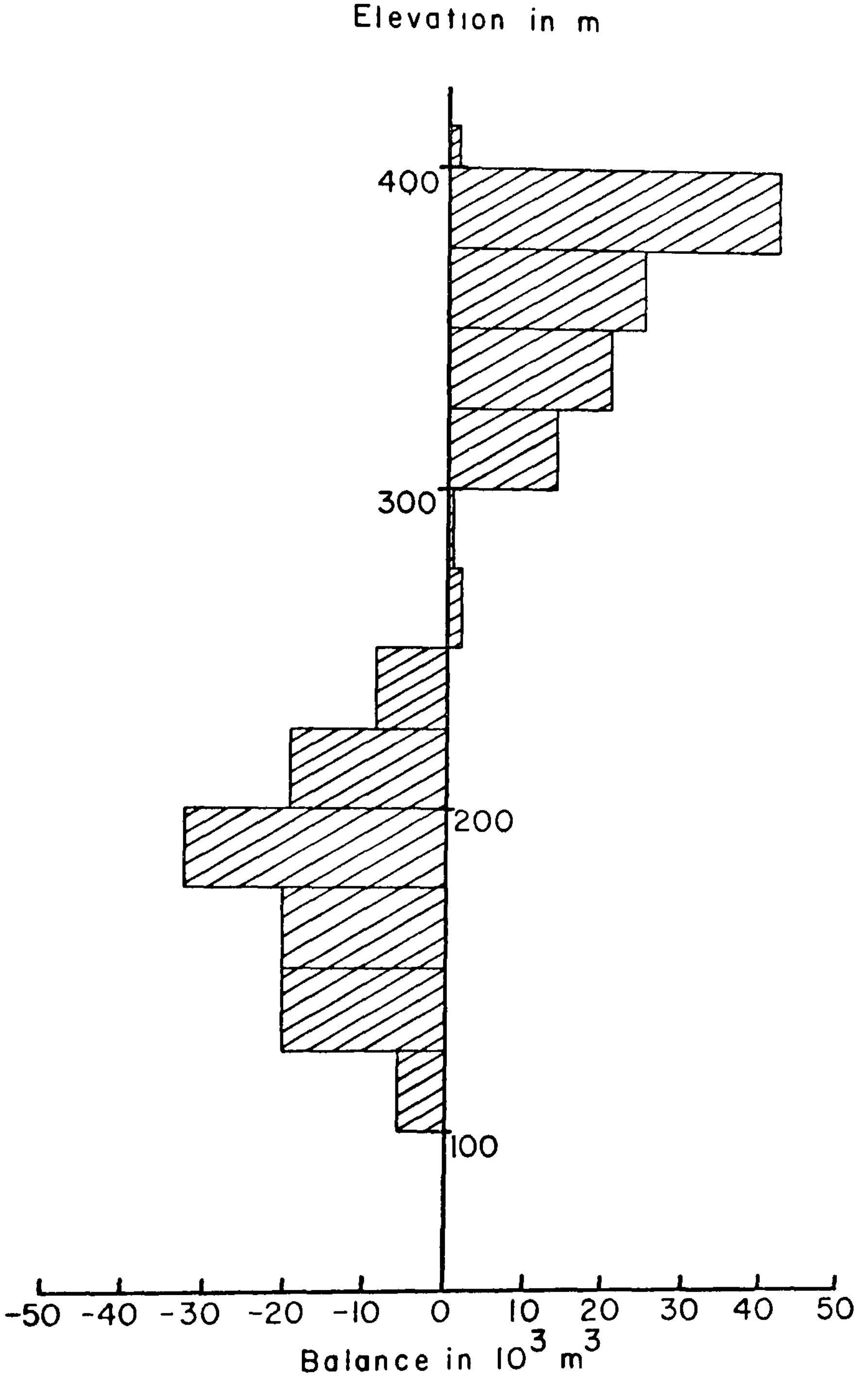

Figure 23. Areal mass balance of glacier G 1 for 1968-1969. For symbols see Figure 24.

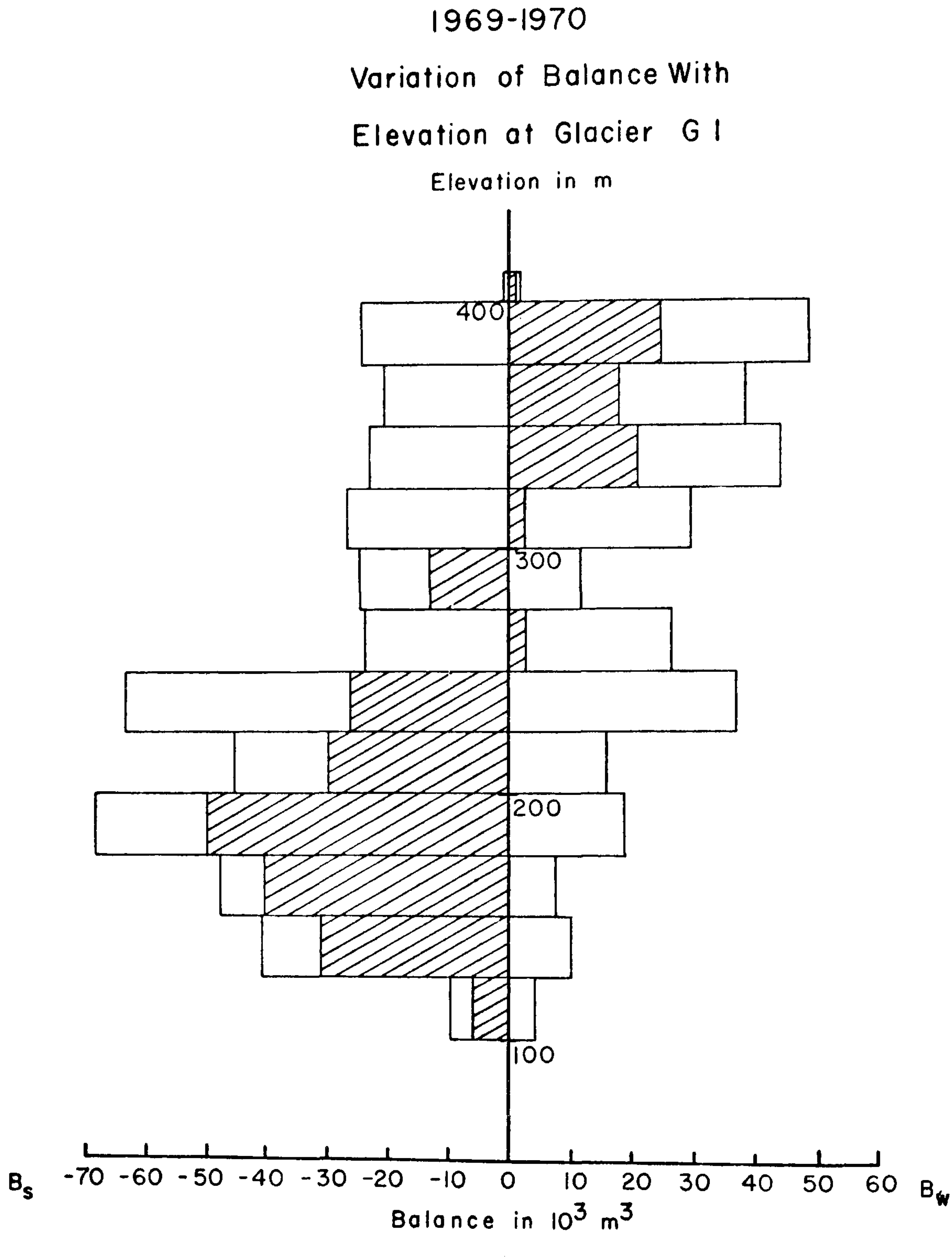

Figure 24. Areal mass balance of glacier G 1 for 1969-1970. Hatched area shows the areal balance change, unhatched columns represent areal summer balance, B_S, and areal winter balance, B_W.

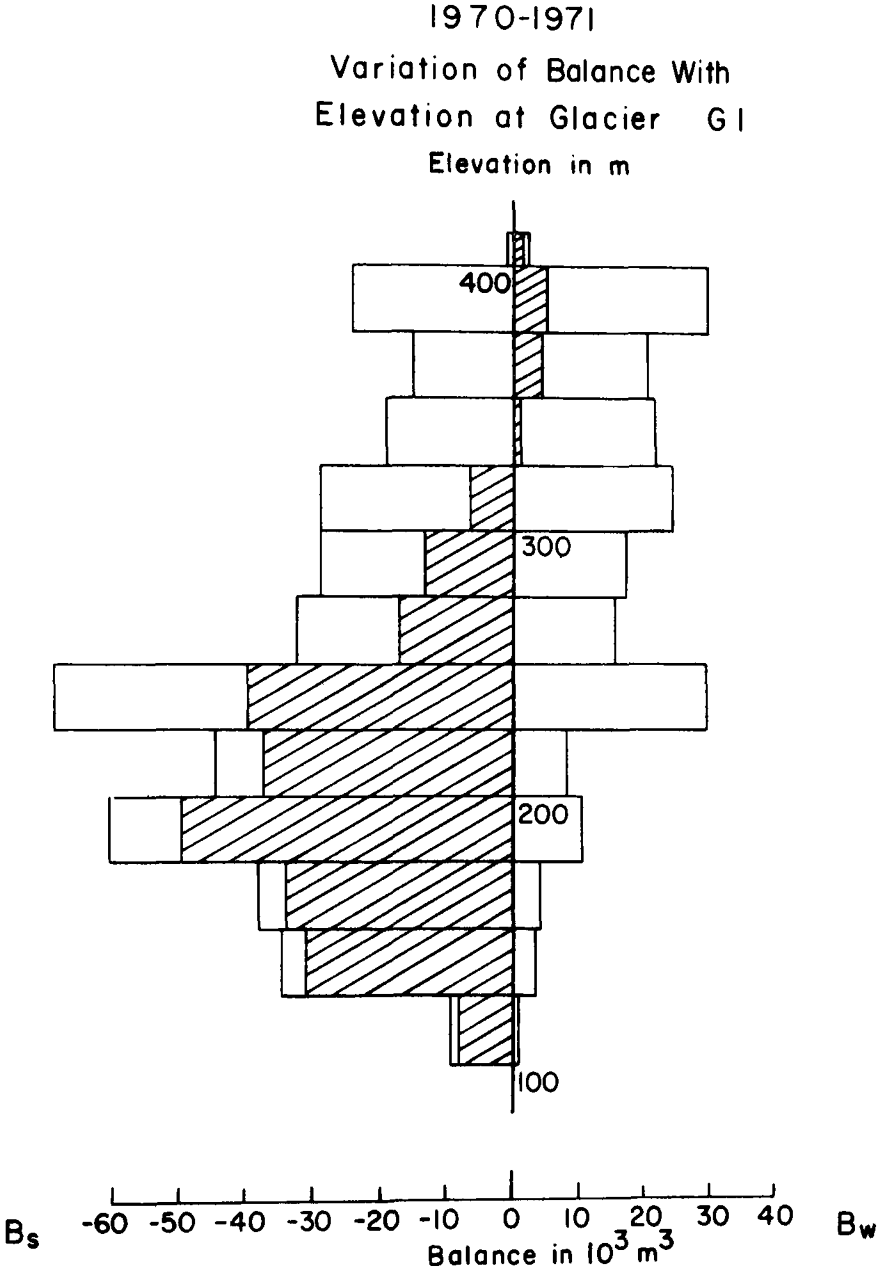

Figure 25. Areal mass balance of glacier G 1 for 1970-1971. For symbols see Figure 24.

steady-state balance curve at the equilibrium line, which raises several difficulties in application, particularly for mass balance studies with a dense network of measurements. Such studies often give balance curves whose slopes range widely with elevation, so that small errors in the elevation of the equilibrium line produce large differences in the activity index. On some glaciers there may be more than one elevation where the balance is zero, so that the index cannot be defined, and the definition is difficult to apply to a glacier that is undergoing change in dimension. All these difficulties are avoided when the average gradient of the net balance curve is used. It is suggested that this gradient is termed the "mean activity index." This gradient (and the mean gradients of winter and summer balances) should ideally be determined as the mean of the balance gradients for each elevation interval, weighted according to the area of each interval. An approximate, but simpler method of finding it is to use the balance curve unweighted, but to ignore the upper and lower sections of the balance curve, which commonly represents only small parts of the total glacier area.

Heat Balance of Glacier G 1

A precise and complete heat balance study was outside the scope of this project. Some meteorological data, however, were obtained which permit the approximate calculation of the importance of the major heat sources and a determination of the relationship between summer balance and degree-days.

Casella thermohygrographs, Lambrecht totalizing anemometers, Robitzsch actinographs, and precipitation gauges were operated in 1970 and 1971 at the Argentine station. (Meteorological data were also collected in 1969, but that year is not considered in the following treatments because of the short measurement season.) A thermograph, actinograph and totalizing anemometer were operated on G 1 at 200 m elevation during the 1970-1971 summer. Albedo measurements with an Eppley radiometer were made on various parts of the glacier in 1971, giving values from 0.1 for completely dirt-covered ice to 0.55 for the cleanest snow.

The relative contribution of heat from radiation can be calculated from the heat balance equation, provided the long wave radiation balance, R, is known. This was calculated as -2000 $kJm^{-2}d^{-1}$ for each of the years, from the formula $R = R_O\left(1-k\left[\frac{c}{10}\right]^2\right)$ ($cal\ cm^{-2}min^{-1}$) (Hoinkes and Untersteiner, 1952). The cloudiness in tenths, c, averaged about 8.5, and the constants R_O and k were taken as 0.1 and 0.8 respectively, based mainly on values given by Andrews (1964) for a comparable situation at Axel Heiberg Island in the Canadian Arctic. Table 2 gives the average contribution of radiation for the periods of overlap between meteorological and mass-balance observations in each of the summers.

Table 2. Contribution of radiation to heat used for melting at glacier G 1.

(All heat values are given in kJ m^{-2})

Period	Heat used for melting at 200 m a.s.l.	Incoming short wave radiation	1-Albedo	Outgoing long wave radiation	Contribution of radiation balance
Jan 10-29 1970	134 000	217 000	0.7	38 000	83%
Dec. 23, 1970- Jan. 19, 1971	194 000	359 000	0.7	56 000	100%

The 1971 value is the more precise of these figures, and the error in the figures is probably between 10 and 20 percent. The heat transfer by radiation is clearly of overriding importance among the heat sources, which is not surprising in view of the low air temperatures. (Temperature measurements indicate that the temperature in January on G 1 at 200 m elevation is about -0.5° or 1.7°C lower than at sea level.) Condensation of water vapor is probably as important as the convective heat transfer from the air in accounting for the remainder of the heat supply.

The relationship between summer balance, b_s, at various elevations and degree-days at the Argentine station can be expressed as $b_s = D\epsilon$, where D is the degree-days (the sum of the mean daily temperatures above 0°C) at the Argentine station for the measurement period, and ϵ is a variable factor, depending mainly on elevation. The relationships for the same periods as before, for the two years, are given in Table 3.

The values of b_s for 300 and 400 m in 1970 are approximate and are partly based on interpolation, because not all the stakes were measured on exactly the dates indicated. It is apparent from the table that the ranges of ϵ for the two periods are relatively small at a given elevation, so that ϵ can be considered as quasi-constant for the periods.

A quasi-constant relationship between summer balances and degree-days (but with different values for ϵ) has been found in many other studies; e.g. Schytt (1955, p. 46) for Thule, Greenland; Schytt (1964, p. 277) for Nordaustlandet, Svalbard; Liestøl (1967, p. 34-46) for Storbreen, Norway; and Orheim (1970, p. 24) for Store Supphellebre, Norway. Hoinkes and others (1968), who studied Hintereisferner, Austria, also correlated summer balance and degree-days, but adjusted the latter for summer snowfall, which changes the balance, as well as affecting the ablation rate by increasing the albedo. These five studies represent a wide variety of climatic environments. For example, the contribution of the radiation balance to the total heat transfer to the glacier varies considerably, from close to 100 percent at Hintereisferner, to about 25 percent at Store Supphellebre.

Degree-days are a good measure of the heat transfer to all of these glaciers despite such differences in the heat sources simply because air temperatures and radiation are not independent, but show (at least for the summer) high positive correlations (<u>see for example</u> Discussion, by Lister and by Hoinkes, <u>in</u> Hoinkes and others, 1968, p. 253-254). Thus either measure could be used to estimate the summer balance. (From Table 3 it can be seen that the relationship between summer balance and radiation balance was approximately constant for the 1970 and 1971 summers.) For the purpose of the following section, however, where the net mass-balance record is compared with meteorological observations, the degree-day concept is the more useful, because no other radiation balance measurements have been made on Deception Island, whereas there are temperature observations back to 1944.

Table 3. Relationship between degree-days and summer balance.

Period	Degree-days	200 m a.s.l.		300 m a.s.l.		400 m a.s.l.	
	D	b_s	ϵ	b_s	ϵ	b_s	ϵ
Jan 10-29 1970	45	0.40	0.0089	$\approx$ 0.20	0.0044	$\approx$ 0.05	0.0011
Dec. 23,1970-Jan. 19,1971	71	0.58	0.0082	0.26	0.0037	0.11	0.0015

RELATIONSHIP BETWEEN VARIATIONS IN NET MASS BALANCE AND LOCAL CLIMATE

The net mass balance, b_n, is the sum of the positive winter balance, b_w, and the negative summer balance b_s. As shown above, b_s can be expressed as $D\epsilon$ where ϵ may be variable. Thus

$$b_n = b_w + D\epsilon$$

and it is desired to test the measured record of b_n against b_w and $D\epsilon$.

A measure of the degree-days for each of the summers from 1944 to 1967 was found by planimetry of the area above 0°C of the curves of mean monthly temperatures. The meteorological data available do not permit a determination of b_w, so that a direct calculation of b_n is not possible. However, there is a significant negative correlation between $D\epsilon$ and b_n as determined from the stratigraphic record ($r = -0.55$, $P < 0.01$) (Fig. 26). This indicates that the variations in b_n are controlled mainly by variations in D.

Linear regression analysis of b_n against D shows that the best fit is given by the line

$$b_n = 0.71 - 0.0016D$$

The value for ϵ is close to those given previously for the 1969-1970 and 1970-1971 summers (0.0011 and 0.0015) for 400 m elevation at G 1. The ice recorded in the fissure section, as deposited between 1944 and 1969, originated also at about 400 m elevation. The close correspondence in values for ϵ suggests that the year-to-year variations in the product $D\epsilon$ are mostly determined by variations in D. Thus the variations in net balance from 1944 to 1967 are mostly due to the variations in summer balance, and these in turn are closely related to variations in summer degree-days.

That the summer balance variations are closely related to the variations in summer degree-days at Deception Island is now well established, and accords with the results from the many other areas quoted above. The concept that the summer balance variations account for most of the variations in net balance also seems of general applicability. The relationship was tested by a consideration of the few long records available of observations of winter and summer balances. For Storglaciären, Sweden (Kasser, 1967; V. Schytt, personal communication, 1971) for the 25 balance years 1946 to 1970, $\bar{b}_w$ varied from 0.66 m to 2.16 m, with a mean, $< \bar{b}_w > = 1.23$ m and a standard deviation, $\sigma = 0.35$ m, and $\bar{b}_s$ varied from $- 0.75$ m to $- 3.00$ m, with the mean $< \bar{b}_s > = - 1.77$ m, and $\sigma = 0.56$ m. At Storbreen, Norway, from 1949 to 1965 (Liestøl, 1967) $\bar{b}_w$ was between $+ 0.96$ m and $+ 2.28$ m, with $< \bar{b}_w > = 1.36$ m and $\sigma = 0.32$ m,

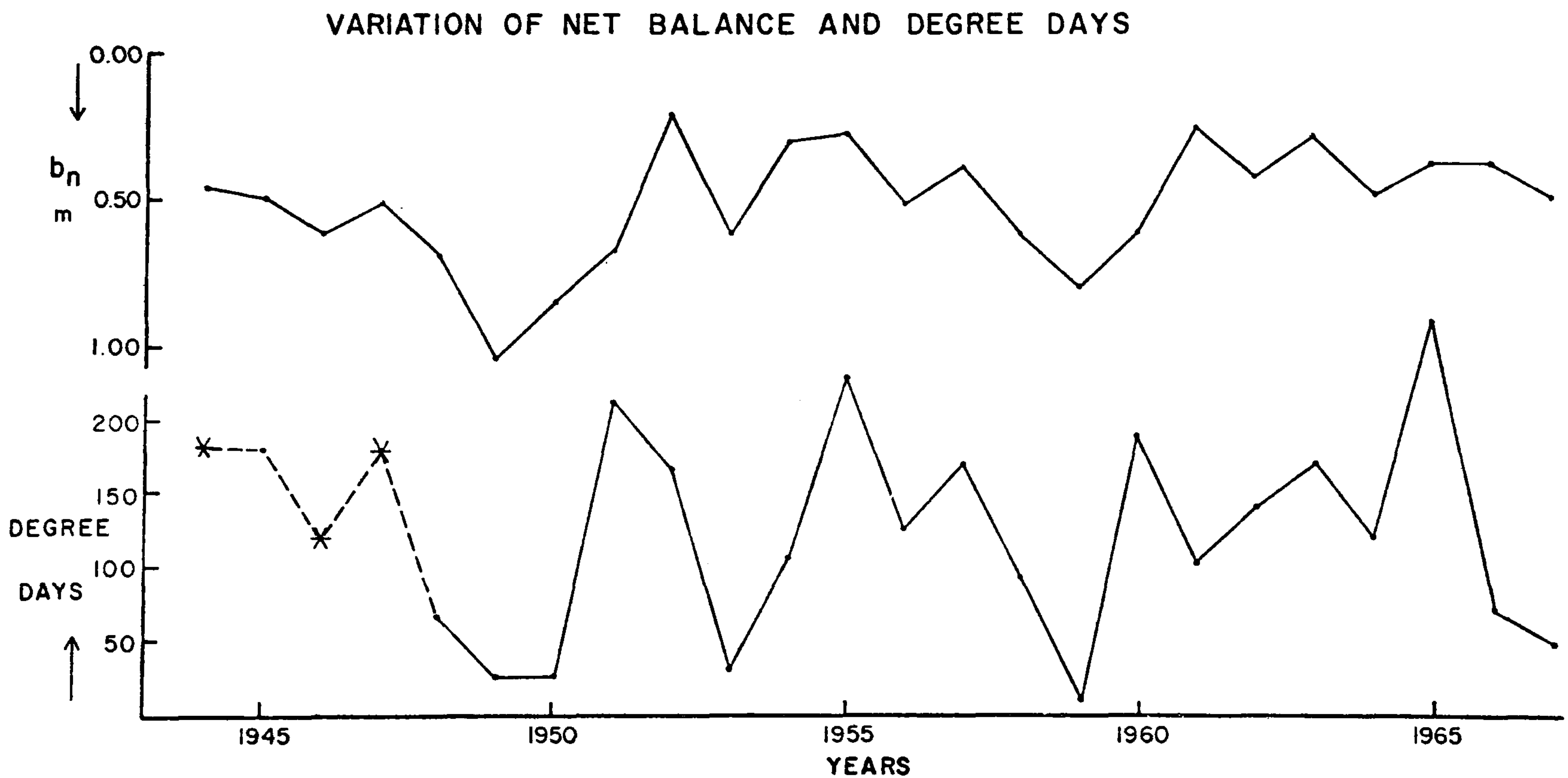

Figure 26. Net balance at the fissure and degree days at the British station from 1944 to 1967. A measure of the degree days was found by planimetry of the curves of mean monthly temperatures. The starred points represent years where data for one or more months were missing. In these cases the temperature has been found by interpolation from Orcadas at Laurie Island, the nearest active station.

and b_s varied from - 0.82 m to - 2.35 m, $< \bar{b}_s > = - 1.68$ m, $\sigma = 0.46$ m. For Sarennes Glacier (Kasser, 1967), for the 17 balance years 1949 to 1965, $\bar{b}_w$ varied from + 0.71 m to 2.50 m, $< \bar{b}_w > = 1.49$ m, $\sigma = 0.47$ m, and $\bar{b}_s$ varied between - 1.00 m and - 3.70 m, $< \bar{b}_s > = - 2.22$ m and $\sigma = 0.77$ m. Thus the variations in summer balance exceed those in the winter balance for all these glaciers. The ratio of standard deviation to the mean values are, however, remarkably similar for the summer and winter balances. The ratio $\sigma_{b_s} / < \bar{b}_s >$ equals 32 percent for Storglaciären, 27 percent for Storbreen and 35 percent for Sarennes, and for each of the glaciers the ratio $\sigma_{b_w} / < \bar{b}_w >$ is exactly 3 percent less.

The glaciers considered, including Deception Island, are between 45° and 70° latitude, in situations of seasonal differences in climate. For these climatic environments the summer conditions are more important for the net balance than the winter conditions.

It must also be recognized that the effects of the summer and winter conditions are not independent. Changing the length of the summer not only changes the total ablation (other factors being equal), but it also affects the winter balance by determining whether the precipitation will fall as snow or rain. Also the magnitude of the winter balance will affect the time at which ice and firn is exposed to the radiation, with a corresponding increase in ablation rates because of lowered albedos. There is, furthermore, a feedback effect from one year to the next in the ablation areas of the glaciers; a year of positive balance will leave firn in the ablation area, which again because of the albedo difference, will lower the ablation rate until it is melted off. For the net mass balance record of Deception Island only the first of these effects is important, as the record originates in the accumulation areas of the glaciers, where the winter snow is rarely melted off.

The significant negative correlation between the annual net balances and the annual summer degree-days also provides an independent confirmation of the stratigraphic interpretation from 1944 to the present. The records generally cease to have a significant correlation when the dates of the mass balance record are changed, either by a relative shift of the records, or by the introduction of missing years in the balance record. Only when a missing year is introduced in the oldest part of the mass balance record (leaving the majority of the dates unchanged) does a significant correlation remain. This correlation, however, is less significant than the correlation obtained with no changes in the dating, with the exception of the year 1950-1951. When a missing year is introduced at that point the correlation equals the original correlation.

A missing year ought to show up in the stratigraphy by an unusually thick dirt layer. The dirt layer assigned to 1951 is of normal size, which suggests that there was not a year of negative balance in 1950-1951. Unfortunately this year is in part of the fissure section that contains dispersed particles (Fig. 6), and where the stratigraphic interpretation is not completely certain. In fact the 1950-1951 ice layer contained the only layer of particle concentration in the whole stratigraphic section that was not counted as an annual marker; instead it was tentatively interpreted as being formed by particle seepage. Dividing the 1950-1951 layer into two years gives a reduced correlation between mass balance and degree-days so that the original interpretation is preferred. This conclusion is also supported by the climatic observations on the 1949-1952 expedition at Maudheim (71°S, 11°W). Schytt (1958) states that the 1950-1951 net mass balance was about average for the period 1935-1951, and that the 1950-1951 summer was unusually cold.

The preceding has shown that from 1944 to 1967 the Deception Island annual balances determined from the stratigraphic record are controlled mainly by the summer temperatures. Before the record is compared with records from other areas a test must be made of whether the local climate of Deception Island is representative of a larger region. And because the net mass-balance record reflects mainly the summer temperatures, it is most appropriate to test this question by comparing summer temperatures for different areas.

RELATIONSHIP BETWEEN SUMMER TEMPERATURES FROM 1945-1946 TO 1970-1971 FOR MIDDLE TO HIGH LATITUDE STATIONS IN THE SOUTHERN HEMISPHERE

The mean temperatures for the summers (December-February) 1945-1946 to 1970-1971 have been compared for the following 15 stations between 35°S and 70°S: Deception Island, Argentine Island, Orcadas (Laurie Island), Stanley (Falkland Islands), Punta Arenas (Chile), Grytviken (South Georgia), Gough Island, Tristan da Cunha, Marion Island, Port-aux-Français (Kerguelen Islands), Hobart (Tasmania), Macquarie Island, Campbell Island, Dunedin (New Zealand), and Invercargill (New Zealand). Data for 307 out of the possible 390 summers were available for this comparison. The data were obtained from World Weather Records (U.S. Weather Bureau, 1959, 1966, 1968), and from Monthly Climatic Data for the World (U.S. Weather Bureau, 1961 to 1971).

The correlation coefficients computed when these stations are compared in pairs, and the probabilities of the correlations, are shown in Table 4. The probabilities of these correlations, and of all other correlations discussed in this report, are evaluated using Student's t distribution, with

$$t = r\sqrt{(N - 2)}/\sqrt{(1 - r^2)} \text{ , where}$$

r is the correlation coefficient, and N the sample size. The calculated t is tested at the probability levels of 0.20, 0.15, 0.10, 0.05, 0.02, 0.01, and 0.001. Thus when the probability of a correlation is given as, for example < 0.05, it means that this correlation has less than 5 percent, but greater than 2 percent, probability of arising by chance.

All correlations with a probability < 0.20 are included in Table 4. Although the time period is short and the distribution of stations is limited, significant patterns do appear. Deception Island shows significant positive correlations with the other stations in the southwest Atlantic Ocean (Orcadas, Stanley, and Grytviken, situated between 52°S and 63°S and 60°W and 36°W) and with Argentine Island (65°S, 64°W). There is also a tendency for the variations at the 15 stations taken in pairs to show positive correlations when the stations are situated in similar latitudes, whereas stations more than 10° of latitude apart generally show no correlations. Thus variations in the summer temperatures, and net mass-balance variations, at Deception Island reflect the regional climate in the southwest Atlantic Ocean, and these variations are to some degree representative of the climatic variations in the southern hemisphere between approximately 55°S to 70°S.

The relationship between the various stations is further illustrated in Figs. 27 and 28, which show mean temperatures for 5-year intervals, and 5-year running means (binomial smoothing) of the temperatures, respectively. It again appears that in many cases stations in

Table 4. Correlations between summer temperatures at 15 stations in the southern hemisphere.

Station / Geogr. coord. \ Station / Period of data	Argentine I. 1951 - 1971	Orcadas 1945 - 1971	Grytviken 1945 - 1971	Stanley 1945 - 1971	Punta Arenas 1945 - 1971	Tristan da C. 1945 - 1951	Gough I. 1955 - 1971	Marion I. 1948 - 1971	Port aux F. 1951 - 1971	Hobart 1945 - 1971	Macquarie I. 1948 - 1971	Campbell I. 1945 - 1971	Invercargill 1950 - 1971	Dunedin 1945 - 1961
Deception I. 63°S, 61°W	0.64 13 <0.001	0.81 18 <0.001	0.44 18 <0.10	0.37 19 <0.15							0.35 18 <0.20			
Argentine I. 65°S, 64°W		0.54 16 <0.05									0.35 18 <0.20	0.34 18 <0.20		
Orcadas 61°S, 45°W			0.51 22 <0.02			0.38 13 <0.20			-0.44 16 <0.10					
Grytviken 54°S, 37°W					0.32 18 <0.20			0.34 21 <0.20		0.30 21 <0.20				
Stanley 52°S, 58°W					0.65 19 <0.01									
Punta Arenas 53°S, 71°W								-0.37 17 <0.20				0.30 20 <0.20		
Tristan da C. 37°S, 12°W							0.91 6 <0.02							
Gough I. 40°S, 10°W									0.73 11 <0.02				0.75 13 <0.01	
Marion I. 47°S, 38°E										0.53 20 <0.02			0.35 20 <0.20	
Port aux F. 49°S, 70°E										0.49 14 <0.10			0.65 17 <0.01	
Hobart 43°S, 147°E														
Macquarie I. 54°30'S, 159°E												0.84 22 <0.001	0.35 19 <0.20	
Campbell I. 52°30'S, 169°E													0.61 20 <0.01	0.59 16 <0.02
Invercargill 46°S, 168°E														0.83 11 <0.001

Reading vertically, the numbers show: the correlation coefficient, the number of years correlated, and the probability of the correlation. The values are only given where the probabilities < 0.20. The only two negative correlations are enclosed in squares. Dunedin is situated at 46°S, 170°W.

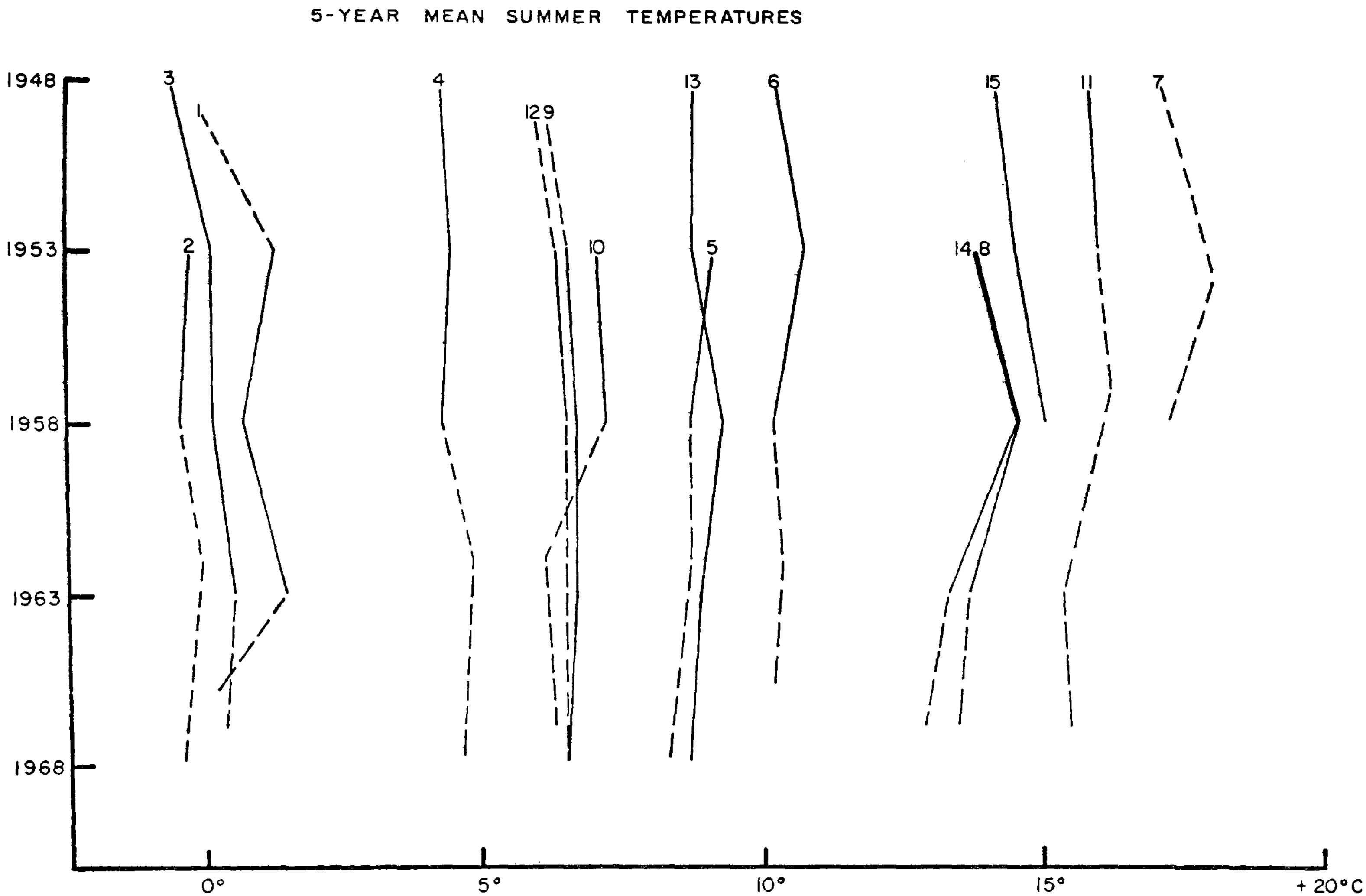

Figure 27. Mean summer temperatures (December-February) for 5-year intervals for 15 stations in the southern hemisphere. 1 = Deception Island, 2 = Argentine Island, 3 = Orcadas, 4 = Grytviken, 5 = Stanley, 6 = Punta Arenas, 7 = Tristan da Cunha, 8 = Gough Island, 9 = Marion Island, 10 = Port-aux-Français, 11 = Hobart, 12 = Macquarie Island, 13 = Campbell Island, 14 = Invercargill, 15 = Dunedin. For geographic locations see Table 4. Dashed portions of the curves are cases of imcomplete data. Each point is plotted for the middle of the time interval covered.

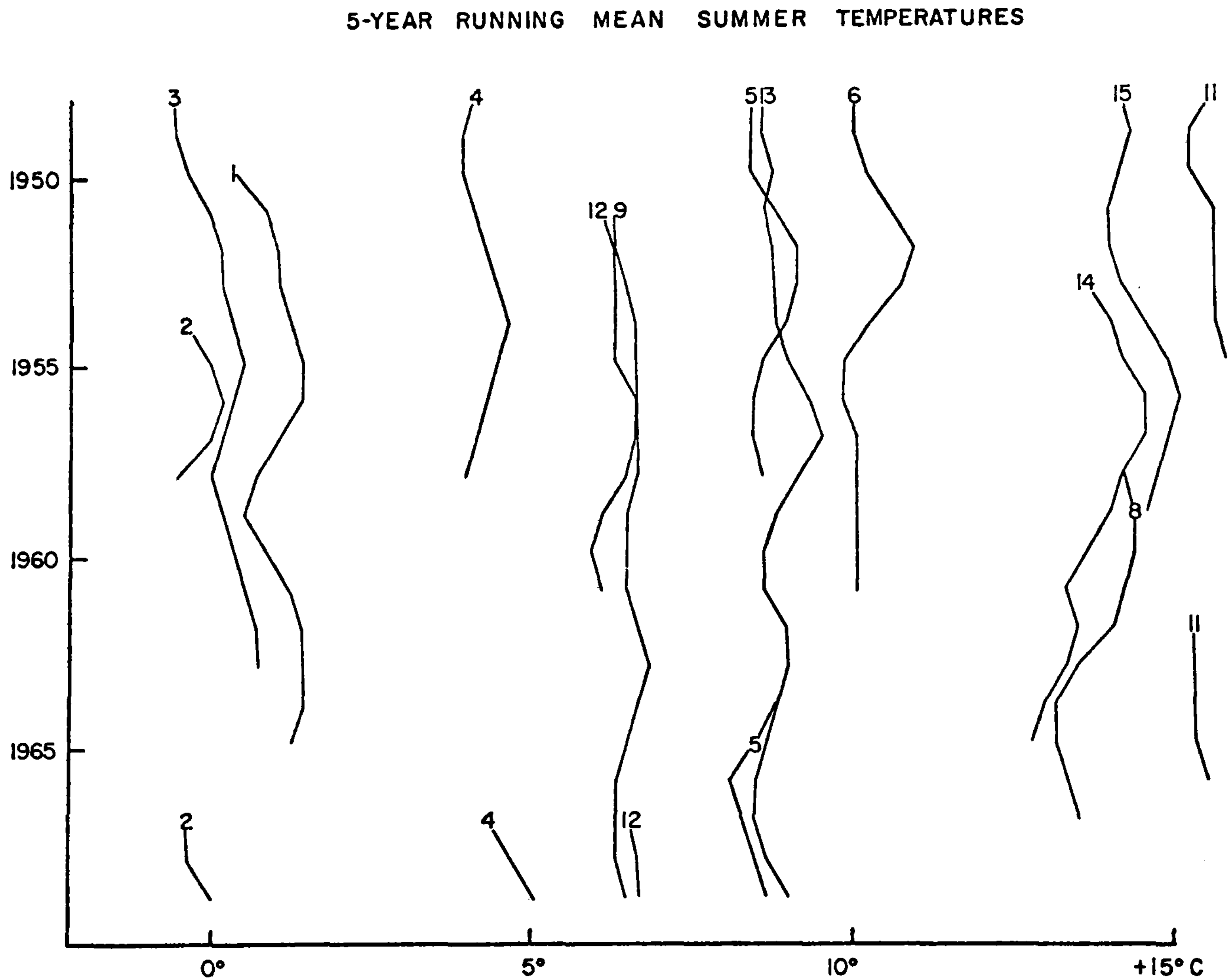

Figure 28. 5-year running means (binomial smoothing as in Fig. 15) of summer temperatures (December-February) for stations in the southern hemisphere. For identification of stations see Fig. 27. All running means represented are based on five years of data.

similar latitudes show similar behavior, although the limited number of data points available after the data are grouped over 5-year periods make any conclusion tentative.

We now proceed to compare the net mass-balance record of Deception Island with records from other areas. First, the record is compared with net mass-balance records, both based on surface observations and determined by other means. Second, the record is tentatively interpreted in terms of climatic elements (primarily summer temperatures), and the variations in these are compared with known variations elsewhere.

COMPARISONS BETWEEN NET MASS-BALANCE RECORD FROM DECEPTION ISLAND AND NET MASS-BALANCE RECORDS FROM OTHER AREAS

Comparison With Net Mass-Balance Records Based on Surface Observations

Net mass-balance records can be obtained by various techniques, but the only completely reliable method is by direct surface observations on glaciers. The longest continuous record of this kind dates from the 1946 mass balance year, and is for Storglaciären, Sweden. The mean mass balances for 5-year intervals from 1946 to 1970 for three areas in the northern hemisphere and for Deception Island are shown in Fig. 29. All mass-balance records of at least 15 years of continuous surface observations are included in the three curves for the northern hemisphere. The curve for northwestern U.S.A. is from South Cascade Glacier. The curve for Scandinavia is the mean for Storglaciären (Sweden) and Storbreen (Norway). The curve for the European Alps is the mean for the three glaciers Sarennes (France), Hintereisferner (Austria) and Aletschgletscher (Switzerland). The record for Aletschgletscher, however, is calculated from hydrological observations and may not be as precise as the other records. The mean for each region is used because within each region the annual balances of the glaciers mentioned show very high positive correlations ($r = +0.69$, for Scandinavia, $+0.91$, $+0.89$, $+0.73$ for the three pairs from the Alps, $P < 0.001$ for all correlations, see Table 5).

Figure 29 shows that the variations in the 5-year means of mass balance for Deception Island are out of phase with those of the three regions in the northern hemisphere. The out-of-phase behavior is further illustrated in Fig. 30 which shows 5-year running means (binomial smoothing) of the Deception Island record compared with the combined record (with similar smoothing) from the three northern hemisphere regions ($r = -0.76$, $P \approx < 0.01$; see comments on the probability of the correlations on p. 72).

Two differences between the northern hemisphere records and the record from Deception Island must be noted in this connection. First, the northern and southern hemisphere balance years differ by 6 months (the balance year lasts from autumn to autumn). Second, the northern hemisphere records are based on the mean net balance for the whole glacier surface, whereas the Deception Island record represents part of the accumulation area. There are no avalanches on the Deception Island glacier, and the mass-balance variations in the accumulation area can be expected to parallel the variations for the whole glacier. Only in exceptional years will this not be the case. When the records are averaged over 5-year intervals, as in Figs. 29 and 30, the influence of any such exceptional years and of the time difference between the hemispheres becomes very small, and does not invalidate comparisons of the records.

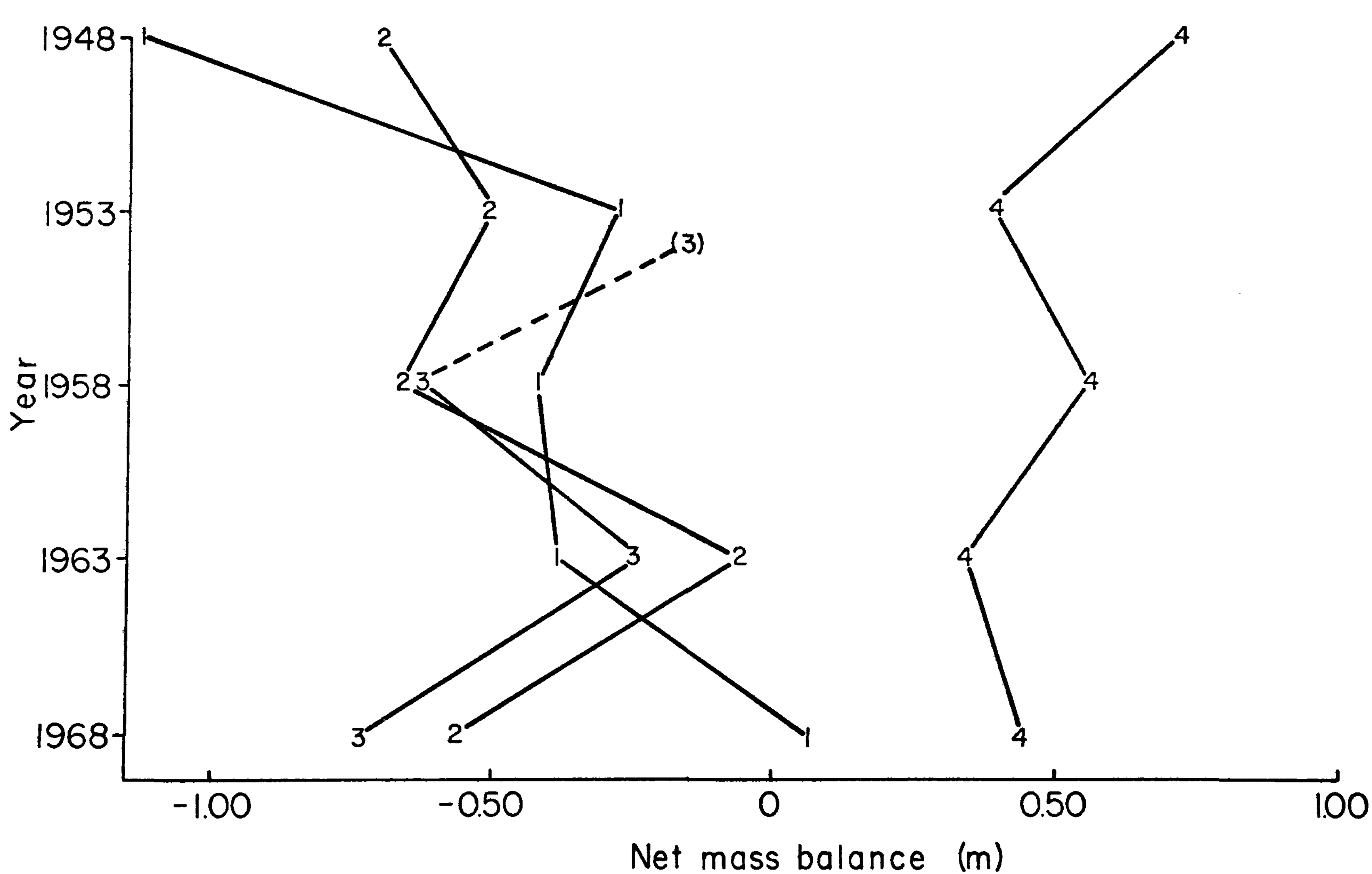

Figure 29. 5-year mean net balances from 1946 to 1970. 1 = European Alps, 2 = Scandinavia, 3 = NW U.S.A., 4 = Deception. The means are plotted for the middle of each period.

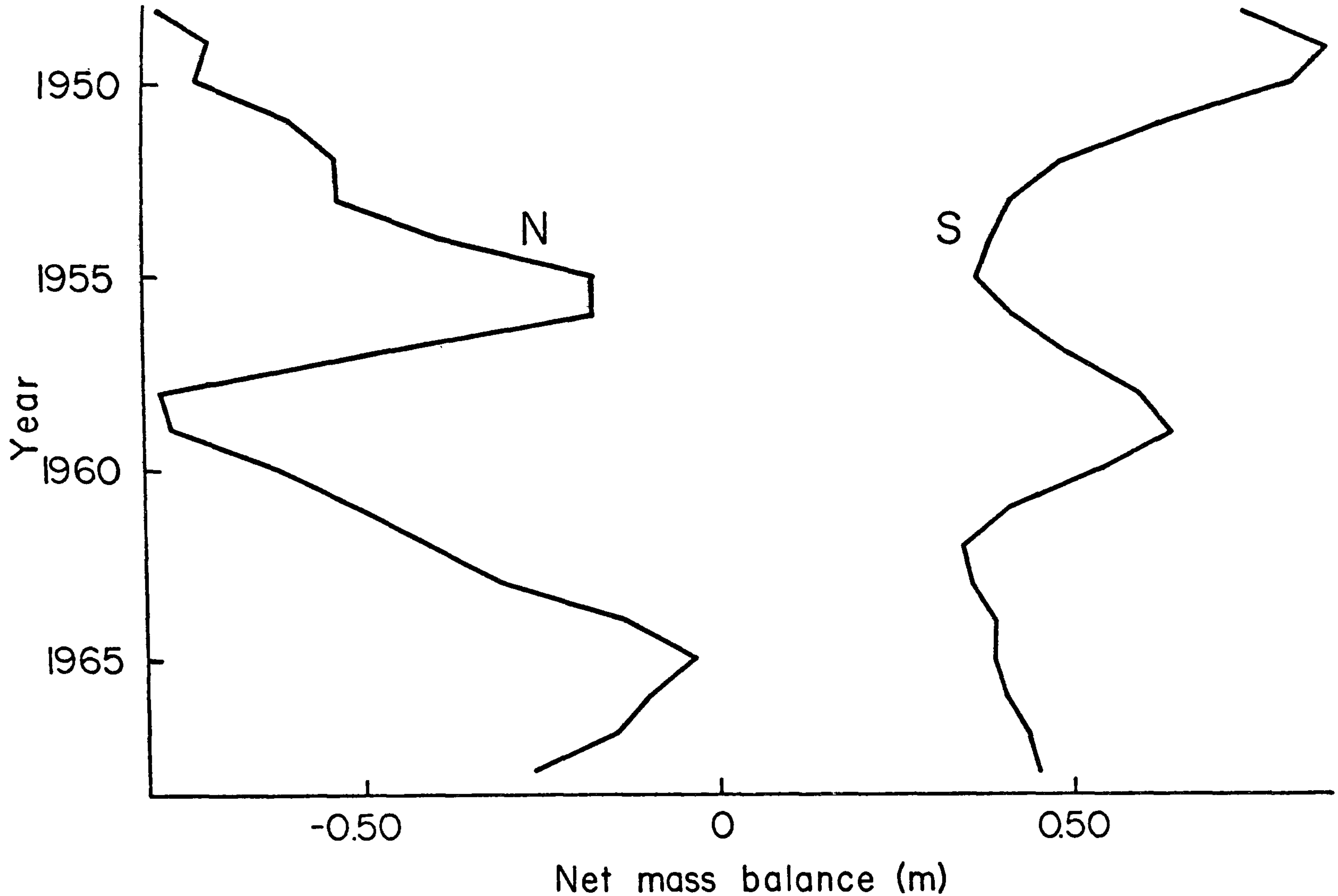

Figure 30. 5-year running means of the combined record from the three northern hemisphere regions (see Fig. 29), and the Deception record, from 1946 to 1970. The running means are smoothed by the binomial function used for Fig. 15.

Table 5. Correlations between annual mass balances from 1946 to 1970.

	Sarennes 1949-1970	Hintereis 1953-1970	Storbreen 1949-1970	Storglac. 1946-1970	IGAN 1958-1967	S. Cascade 1953-1971	Deception 1946-1971
Aletsch 46°N, 8°E	0.89 22 <0.001	0.91 17 <0.001	-0.09 22	0.15 25	0.32 13	-0.07 17	-0.41 25 <0.05
Sarennes 45°N, 6°E		0.73 18 <0.001	-0.31 22 <0.20	-0.31 22 <0.20	0.34 13	-0.27 17	-0.54 22 <0.01
Hintereis 47°N, 11°E			0.18 18	0.12 18	0.36 13	0.07 17	-0.34 17 <0.20
Storbreen 62°N, 8°E				0.69 22 <0.001	0.26 13	0.16 17	-0.04 22
Storglac. 68°N, 19°E					0.04 13	0.39 17 <0.15	-0.01 25
IGAN 67°N, 65°E						0.02 12	0.07 13
S. Cascade 48°N, 124°W							-0.06 18

Reading vertically, the numbers show: the correlation coefficient, the number of years correlated, and the probability of the correlation. Only probabilities < 0.20 are shown. The Aletsch record is from 1946 to 1970. Data are missing for 1954 for South Cascade Glacier.

The fact that the net mass-balance variations for these three northern hemisphere regions are in phase (with the exception of the Alps for the last 5-year period, Fig. 29) suggests that the northern hemisphere curves reflect changes in the general climate between latitudes 45°N and 70°N, within which these glaciers are situated. As shown earlier, the Deception Island variations are to some degree representative of the variations between 55° and 70°S. Therefore the following conclusion is drawn for the last 25 years: in the middle to high latitudes (45° - 70°N, 55° - 70°S) the climatic elements that have controlled the mass-balance variations are apparently characterized by short-term antiphase fluctuations in the two hemispheres.

The antiphase fluctuations illustrated in Figs. 29 and 30 seem to be characterized by about a 10-year cycle. Spectral analysis of the Deception Island record confirms that there is an about 10-year cycle of antiphase variations in the records. There is also a suggestion in Figs. 29 and 30 of a longer-period antiphase relationship between the two records, and the spectral analysis also suggests the presence of an antiphase cycle with a period of about 20 years. Obviously, the records are too short to confirm this cycle.

Table 5 shows the results of comparing the annual net mass balances of these seven glaciers plus IGAN glacier in the Polar Urals. IGAN is included although only data for 13 years are available, because a longer record calculated for this glacier is used for comparison in the following section. There are no significant correlations between the annual balances for the northern hemisphere glaciers, apart from the close correlation within each region mentioned earlier. Deception Island shows significant negative correlations with the glaciers in the Alps, but the incomplete time overlap between the records makes it difficult to give this correlation a physical significance. It can be noted that the combined annual mass balance record of all these northern hemisphere glaciers is also negatively correlated with the Deception record ($r = -0.35$, $P < 0.1$), but again there are difficulties with the interpretation caused by the lack of overlap in time.

The 10-year running means of the combined records from the northern hemisphere show high negative correlations compared with the Deception Island record. These correlations seem to be caused by the opposing long-term (about 20 years) trend in the two hemispheres, mentioned above.

The results of these comparisons suggest that the annual balances may be dominated by relatively localized meso-scale weather situations, and that it is necessary to smooth the records over periods of several years to obtain information about possible changes in the general climate affecting all or most records. The above comparisons have indicated both a 10-year antiphase cycle in the climatic factors affecting the mass balances in the two hemispheres, and have suggested opposing longer-term trends. Climatic "cycles" are often short-lived, however, and it is necessary to test whether these conditions also existed before 1946.

Comparison With Long-Term Net Mass-Balance Records

There are apparently only six published records, in addition to the Deception Island record, that give net mass-balance variations for a century or more. Two of these are from the northern hemisphere - Storbreen (Liestøl, 1967) and IGAN (by Khodakov, in Troitskiy and others, 1966) - and four are from the southern hemisphere. These four are all from Antarctica, two from the coast - Little America V (Gow, 1968) and Wilkes (Cameron, 1964) - and two from the interior - South Pole (Giovinetto, 1960) and Byrd (Gow, 1968).

Annual net balances have also been determined at Plateau Station, Antarctica (Koerner, 1971), but the annual values for this record have not been published. No attempt was made to obtain the unpublished values as this record is probably not very precise because of the high incidence of missing years due to a very low mean annual net balance (< 0.025 m).

The six long records, and a shorter record from Aletschgletscher, are compared in the following with the Deception Island record. But before the results are discussed it is necessary to consider the confidence that can be placed in each record.

Evaluation of the Quality of the Long-Term Records

The Aletsch record is considered to be the best record of the seven, and is therefore included, although it is shorter than the others. This record is based on observations of runoff from the glacier, combined with precipitation observations in the catchment area. The runoff data are probably quite precise, but large errors can be expected in the precipitation measurements, caused by the considerable difficulties in measuring precipitation, particularly solid precipitation, in mountainous environments. Errors may also be due to inaccuracies in the assumed evaporation, and by internal storage effects (if real) of the sort suggested by Tangborn and others (in press). The annual net balance is the relatively small difference between the runoff and the precipitation (with minor corrections), and it cannot be expected to be very precise. Despite these problems, the record shows a very good correlation with the nearby glaciers Sarennes and Hintereis (Table 5) from 1949 to the present. It is likely that the early part of the record is still less precise than the part compared in Table 5 but it is nevertheless a record based on annual observations on and near a glacier (which none of the following are), and for that reason is considered superior to the following records.

The other two records from the northern hemisphere, Storbreen and IGAN, are both calculated, using relationships between meteorological factors and mass-balance variations determined during recent years. The confidence that can be placed in these records is very different; the Storbreen record is much more likely to reflect accurately past mass-balance variations for five reasons. Firstly, the Storbreen record is based on a longer series of comparisons between mass balance and meteorology (16 years) than is IGAN (11 years), making the relationship established between mass balance and meteorological factors sounder and more significant. Secondly, the relationship used by Liestøl, namely that summer balance is related to summer temperatures and winter balance to winter precipitation, is physically more acceptable than that used by Khodakov, who also relates summer balance to summer temperatures, but relates winter balance to winter temperatures. Hoinkes (1964, p. 415) described a similar attempt by Russian authors, to calculate variations on Novaya Zemlya, to be of little value, and the same may be suspected for the IGAN record. Thirdly, the distances from the glaciers to the meteorological stations used in the calculations are much smaller for Storbreen than for IGAN. The Storbreen record, from 1948 to 1900, is calculated from meteorological observations at Luster weather station 37 km away, and for the period 1900 to 1816 from data from Bergen observatory, 200 km away. The IGAN record is calculated from data from Syktyvkar weather station, situated 1,000 km from the glacier. Fourthly, the Storbreen record is based on two continuous series of observations, whereas there are four missing years (1891, 1893, 1894, 1895) within the Syktyvkar record which began in 1818. In this connection it may be noted that the IGAN record is somewhat misleadingly represented on the apparently only occasion it is presented in an article in the English language; 10-year running means of the record in Grosval'd and Kotlyakov (1969) suggest that fewer years are missing. Fifthly, the changes in glacier mass for Storbreen calculated from the computed mass-balance variations are in remarkably good agreement with the volume changes of Storbreen found from maps of the glacier at three different times, and with variations in the frontal positions of nearby glaciers, taking into account a time lag of about four years. No such tests have been made of the IGAN record.

The confidence that can be ascribed to the Antarctic records also varies considerably. The records from Little America V and from Byrd are both based on core studies, whereas the records from South Pole and from Wilkes are based on examination of pits. Because of the large local variability in net balance, as well as the difficulty of identifying annual diagnostic markers at depth, it is considered that only by pit studies can values for the annual net balances be determined that can be accepted with confidence. For these reasons much less confidence can be placed in the first two records than in the last two. The only record of the four where the errors are discussed is that from the South Pole (Giovinetto and Schwerdtfeger, 1966). For this reason, and because it seems to be based on very careful field work, the South Pole record is considered to be by far the most precise record from the Antarctic continent. Of the other records, Wilkes is best because it, too, is based on pit studies; Little America V is next best. The Byrd record, which is based on less well-developed seasonal stratification than at Little America V, and which also is made up of two core sections from separate holes, is the least reliable.

It is not easy to compare the quality of the northern and southern hemisphere records. Those from the northern hemisphere are precisely dated, but except for Aletsch, are measured away from the glaciers, but are imprecisely dated. The previous considerations indicate, however, that at present the following ranking is reasonable. The Aletsch record is best. The Deception and Storbreen records are second best and of comparable quality, and are followed by the South Pole record. The best records thereafter are Wilkes and probably IGAN, followed by Little America V. The Byrd record is the least reliable. It is considered that the Deception record would be the best of these records if the stratigraphic age of the crater section is confirmed by radiometric dating.

Results of the Comparisons Between the Records

The Byrd record comprises annual mass-balance values back to 1890, with a missing year (1893) where the studies transferred from one core to another, and mean net balances for 5-year intervals from 1890 to 1785. (That there is one missing year is an assumption made by Gow based on the drill depths. It is quite possible that there may be several missing years or none at all.) In the following compilations of correlations the results from Byrd are presented in two parts. The upper values in each table refer to the annual record from 1890 to 1960, and the lower values in parentheses refer to the less certain complete record, which is included where 5- and 10-year means of the records are compared. Similarly, the Storbreen record is presented in two parts. The upper values refer to the record from 1862 to 1970, based on meteorological observations of precipitation and temperature from 1862 to 1948, and from 1948, on the observed net mass-balance values. The lower values, in parentheses, refer to the record from 1816 to the present. For this period only the summer balances are calculated, whereas the winter balances for each year were taken as the mean of the balance from 1862 to the present (Liestøl, 1967).

The correlations obtained among the annual net balances, and the 5-year means, 5-year running means, 10-year means, and 10-year running means of the records are shown in Tables 6-10. Several correlations appear in these tables which are discussed below. But it must be noted that the significance ascribed to the correlations obtained by comparing the unequal-weighted running means (Tables 8 and 10, and p. 65) are approximate. The statistics of these correlations are complicated and have not been precisely determined in this paper. As a first approximate compensation for the autocorrelation in the running mean series, the degrees of freedom, N, used in the probability test (p. 59) have been taken as n/2 for the 5-year running means, and n/3 for the 10-year running means where n is the number of running means correlated.

Comparison of the annual balances of the Deception record with the other records shows no correlations, whereas there are several significant correlations between the smoothed records. Firstly, comparison between the Deception record and the records from the Antarctic continent

Table 6. Correlations between annual values of long mass-balance records.

	L. Amer.V 1856-1959	Byrd 1890-1960	South Pole 1783-1958	Wilkes 1786-1957	Storbreen 1862-1970 (1816-1970)	IGAN 1818-1970	Aletsch 1923-1970
Deception I.	0.01 104	-0.10 69	-0.09 176	0.01 172	0.02 109 (0.03 155)	0.04 149	-0.07 48
L. America V		-0.13 68	0.08 103	-0.06 102	-0.05 98 (-0.04 104)	0.10 100	0.24 37 <0.20
Byrd			0.26 67 <0.05	0.19 66 <0.15	0.13 69	-0.29 66 <0.02	-0.05 38
South Pole				0.05 172	0.11 97 (0.05 143)	-0.08 137	0.15 36
Wilkes					-0.13 96 <0.20 (-0.11 142)	0.05 136	0.11 35
Storbreen						0.01 105 (-0.03 149)	-0.04 48
IGAN							-0.06 48

Reading vertically, the numbers show: the correlation coefficient, the number of years correlated, and the probability of the correlation. Only probabilities < 0.20 are shown.

Table 7. Correlations between 5-year means of long mass-balance records.

	L. Amer. V 1856-1959	Byrd 1890-1960 (17[illegible]5-1960)	South Pole 1783-1958	Wilkes 1786-1957	Storbreen 1862-1970 (1816-1970)	IGAN 1818-1970	Aletsch 1923-1970
Deception I.	0.14 21	-0.08 13 (-0.21 34)	0.14 34	0.05 34	-0.52 21 <0.02 (-0.38 31 <0.05)	-0.16 29	-0.19 9
Little America V		-0.15 13 (-0.08 20)	0.14 20	-0.03 20	0.05 19 (0.03 21)	-0.04 20	0.58 7
Byrd			-0.09 12 (-0.27 33 <0.15)	0.29 12 (0.18 33)	0.04 13 (0.15 28)	-0.15 13 (0.27 27 <0.20)	-0.23 7
South Pole				0.17 35	-0.09 18 (0.06 28)	-0.21 26	0.23 6
Wilkes					0.14 18 (-0.01 28)	0.14 26	-0.11 6
Storbreen						0.18 20 (0.03 29)	-0.17 9
IGAN							0.17 9

Reading vertically, the numbers show: the correlation coefficient, the number of 5-year groups correlated, and the probability of the correlation. Only probabilities <0.20 are shown.

Table 8. Correlations between 5-year running means of long mass-balance records.

	L. Amer. V 1856-1959	Byrd 1890-1960	South Pole 1783-1958	Wilkes 1786-1957	Storbreen 1862-1970 (1816-1970)	IGAN 1818-1970	Aletsch 1923-1970
Deception I.	-0.01 100	-0.25 62 ≈< 0.20	-0.01 172	0.07 168	-0.22 105 ≈< 0.15 (-0.13 151)	0.04 140	-0.21 44
L. America V		-0.12 61	-0.03 99	-0.15 98	0.04 94 (0.03 100)	0.15 91	0.09 33
Byrd			0.08 60	0.20 59	0.08 62	-0.27 61 ≈< 0.15	-0.17 34
South Pole				0.07 168	0.06 93 (0.07 139)	-0.23 128 ≈< 0.10	0.10 32
Wilkes					0.01 92 (0.01 138)	0.05 127	-0.13 31
Storbreen						0.13 96 (0.07 140)	0.15 44
IGAN							-0.04 44

Reading vertically, the numbers show: the correlation coefficient, the number of running means correlated, and the probability of the correlation. Only probabilities < 0.20 are shown, the probabilities are approximate and should not be used without reservations (see page 65).

Table 9. Correlations between 10-year means of long mass-balance records.

	L. Amer. V 1856-1959	Byrd 1890-1960 (1765-1960)	South Pole 1783-1958	Wilkes 1786-1957	Storbreen 1862-1970 (1816-1970)	IGAN 1818-1967	Aletsch 1923-1970
Deception I.	0.01 9	-0.44 7 (-0.31 17)	0.07 16	-0.12 16	-0.44 11 <0.20 (-0.40 15 <0.15)	-0.17 14	-0.85 4 <0.20
L. America V		0.03 6 (-0.01 9)	0.32 10	-0.21 9	0.50 9 <0.20	-0.43 8	
Byrd			0.04 6 (-0.29 16)	0.01 6 (0.09 16)	0.24 7 (0.40 14 <0.20)	0.18 6 (0.45 13 <0.15)	-0.24 3
South Pole				0.19 16	0.10 9 (0.18 13)	-0.18 12	
Wilkes					0.25 9 (0.27 13)	0.35 12	
Storbreen						0.44 10 (0.39 14 <0.20)	0.44 4
IGAN							-0.14 4

Reading vertically, the numbers show: the correlation coefficient, the number of 10-year groups correlated, and the probability of the correlation. Only probabilities < 0.20 are shown.

Table 10. Correlations between 10-year running means of long mass-balance records.

	L. Amer. V 1856-1959	Byrd 1890-1960	South Pole 1783-1958	Wilkes 1786-1957	Storbreen 1862-1970 (1816-1970)	IGAN 1818-1970	Aletsch 1923-1970
Deception I.	-0.03 95	-0.26 57	0.04 167	0.08 163	-0.36 100 ≈< 0.05 (-0.26 146 ≈< 0.10)	0.02 130	-0.18 39
L. America V		0.04 56	-0.04 94	-0.20 93	0.17 89 (0.16 95)	0.07 81	0.08 28
Byrd			-0.11 56	0.39 54 ≈< 0.10	0.01 57	-0.27 56	-0.31 29
South Pole				0.07 163	-0.00 88 (0.06 134)	-0.21 118 ≈< 0.20	0.16 27
Wilkes					0.09 87 (0.06 133)	0.12 117	-0.26 26
Storbreen						0.18 86 (0.09 130)	0.15 39
IGAN							-0.38 39

Reading vertically, the numbers show: the correlation coefficient, the number of running means correlated, and the probability of the correlation. Only probabilities < 0.20 are shown, the probabilities are approximate and should not be used without reservations (see page 65).

reveal only a single, probably insignificant, correlation, namely with the 5-year running means of the Byrd record. Secondly, the smoothed Deception and Storbreen records are all negatively correlated, the least significant being the 10-year means, where the probability of the correlations are 0.2 and 0.15, and the 5-year running means. The upper part of the Storbreen record, from 1862 to the present, shows in most cases more significant correlations with Deception than does the whole record from 1816. One or more of the following explanations may account for this phenomenon:

(1) The early part of the Storbreen record is less precise, because mean winter balance is used for the calculations rather than measured values of winter precipitation.

(2) Before about 1862 the climatic factors causing the antiphase variations between the two records were not present to the same degree.

(3) The antiphase relationship between the two records was present for the whole period, but changes in the age of the lowest part of the Deception record, caused by missing years, result in a relative shift of the records which gives the impression that the antiphase relationship has disappeared. From the estimate of frequency of missing years established earlier (p. 20), there should be about 3 missing years from 1862 to the present, and probably one more between 1862 and 1816. These missing years have <u>not</u> been introduced in the Deception record. An error of 4 years in the assigned dates of the early part of the Deception record would cause the 11-year antiphase cycle to appear almost as an in-phase cycle during the 1816 to 1862 period.

Cross-spectral analysis of the Deception and Storbreen records strongly suggests that the last explanation is both qualitatively and quantitatively correct, and that the antiphase relationship was a reality for the whole period 1816 to the present. The analysis shows that a marked 11-year cycle was present in both the 1816-1862 and the post-1862 periods, but whereas Deception leads Storbreen by about 3.5 years for the period from 1862 to the present, making this relationship out of phase, the two records were in phase for the period 1816 to 1862.

The Deception record is not correlated with IGAN, but it does show one weakly significant (0.2 level) negative correlation with Aletsch. Because the IGAN record is much less reliable than Storbreen or the short Aletsch record it is concluded that the lack of negative correlation between IGAN and Deception does not invalidate the following conclusion: The 11-year antiphase relationship between Storbreen and Deception which probably existed back to 1816, indicates that the antiphase relationship between Deception Island and middle- to high-latitude glaciers in the northern hemisphere, established for the period 1946 to the present, also probably persisted back to 1816. The significance ascribed to this conclusion should obviously be tempered by the fact that only one long reliable northern hemisphere record is available. Long reliable records from other regions of the northern hemisphere are needed before the conclusion can be accepted without reservations.

All other relationships shown in Tables 6 to 10 are statistically much less significant than those between Deception and Storbreen. Most of the correlations are weak and there are no persistent patterns in the relationships between any two pairs of stations. The main features of the correlations are described below, but because of the lack of persistent patterns no conclusions are made.

The records from the Antarctic Continent show a few positive correlations. Annual values for Byrd are positively correlated at the 0.05 level with South Pole, and at the 0.15 level with Wilkes, and the 10-year running means for Byrd and Wilkes are positively correlated approximately at the 0.10 level. However, the 5-year running means of the long Byrd record and South Pole are negatively correlated.

Comparisons between the Antarctic Continent records and the northern hemisphere reveal three, mostly weak, negative correlations between IGAN and the running means for South Pole and for Byrd. The annual values for Byrd are also negatively correlated with IGAN, whereas the long Byrd record shows weakly significant positive correlations with IGAN for 5- and 10-year intervals. The other correlation patterns are weak; the 10-year means for Little America V and Storbreen are weakly positively correlated, as are the annual balances for Little America V and Aletsch. The 10-year means of the long Byrd series and Storbreen are also weakly positively correlated, whereas there is a weak negative correlation between annual values for Wilkes and Storbreen.

Within the northern hemisphere there is one weakly significant positive correlation between 10-year means for Storbreen and IGAN.

The annual variations within the records from the northern hemisphere and from Deception Island (Fig. 31) differ in a major way from those in the Antarctic Continent records (Fig. 32). The 10-year running means shown in Fig. 31 illustrate that within the first group the balance variations for all stations are of comparable magnitude, with variations within the Deception record being the smallest. The variations within the Antarctic records, on the other hand, are an order of magnitude less than those of the Deception record (Fig. 32). This indicates that the Antarctic stations have smaller climatic changes than those reflected in the records from Deception and the northern hemisphere, perhaps because the Antarctic Continent "makes its own climate" (but see also below). Thus the records from Deception and the northern hemisphere glaciers are more valuable than the Antarctic Continent records in providing information on global climatic changes.

One further difference between these two groups of records is that the net balance records from the Antarctic Continent chiefly reflect variations in the year-round precipitation, because little ablation occurs, whereas the Deception record and probably all the northern hemisphere records considered here and in the previous chapter primarily reflect variations in summer conditions. This may provide a further explanation for the difference in magnitude of variations between the

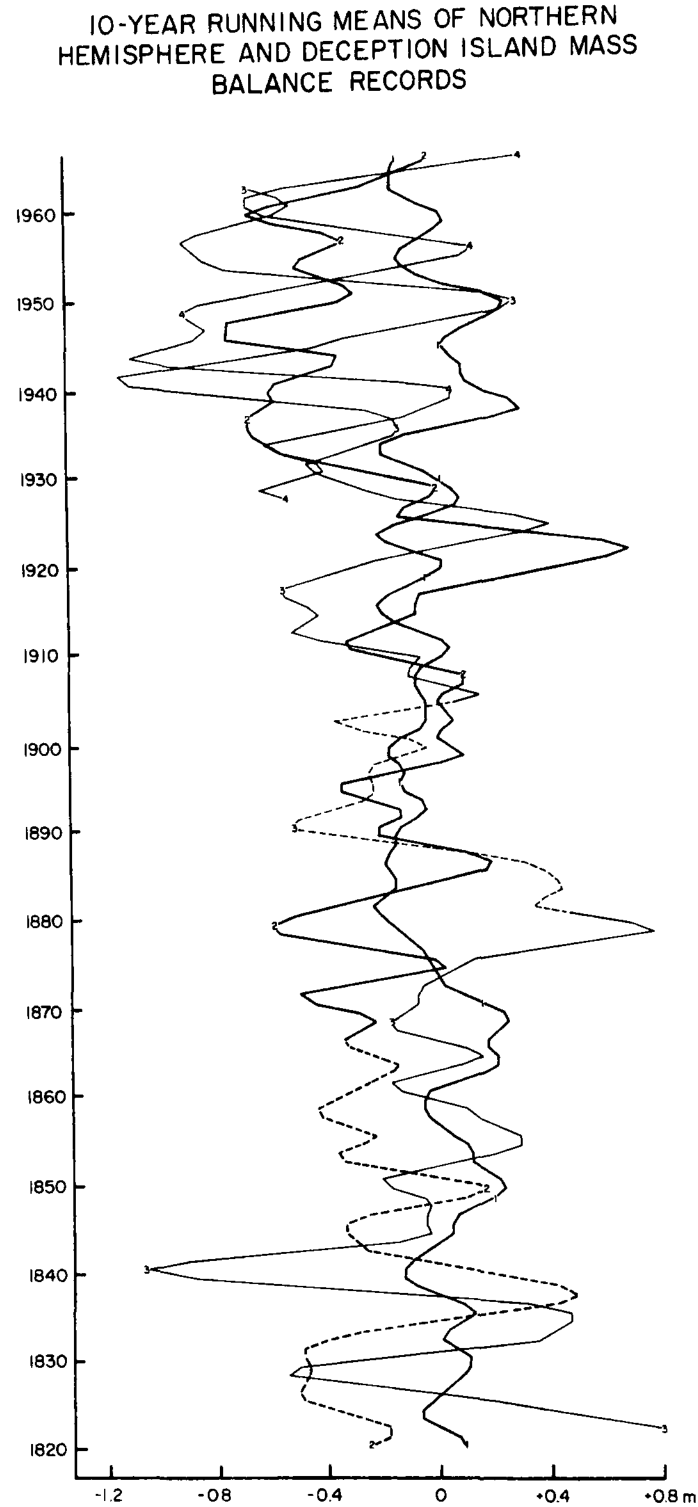

Figure 31. 10-year running means (binomial smoothing as in Fig. 16) of mass balances from Deception Island (1), and three glaciers in the northern hemisphere: Storbreen (2), IGAN (3), and Aletsch (4). Broken lines indicate uncertain or missing data.

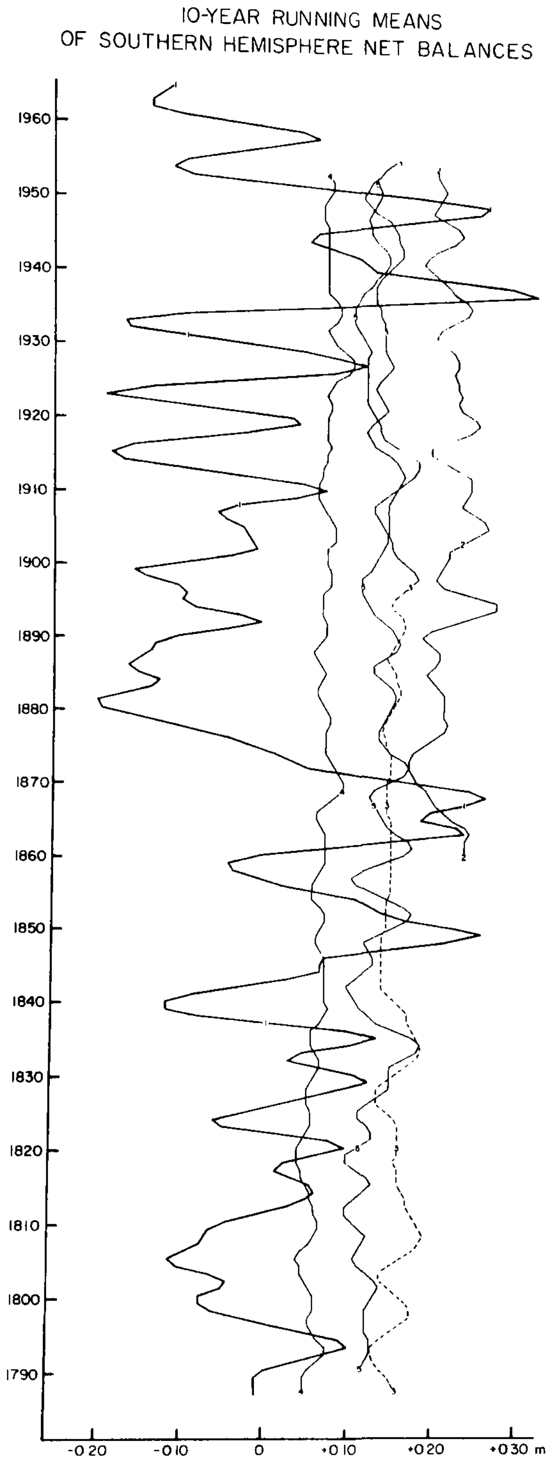

Figure 32. 10-year running means (binomial smoothing as in Fig. 16) of mass balances from Deception Island (1), and four stations on the Antarctic Continent: Little America V (2), Byrd (3), South Pole (4), and Wilkes (5). Broken line indicates uncertain data.

two groups of records; previous considerations have indicated that the year-to-year variations in summer temperatures are larger than those in winter precipitation.

For the above reasons the absence of strong correlations between the records from Deception and those from the Antarctic Continent in Tables 6 to 10 is expected, as are also the much weaker relationships between the northern hemisphere and the Antarctic Continent records than those between the northern hemisphere and Deception.

The foregoing discussion has considered the relationships between the annual balances and the annual balances smoothed over relatively short periods. It is also necessary to consider whether any relationships exist between the long-term variations in the records.

Inspection of Fig. 31 suggests that the Deception record and the northern hemisphere records show a decrease in net balance with time from the last century to the present. Dividing each of the three long records (Deception, Storbreen and IGAN) into two equal parts, and conducting a Variance Ratio test (Table 11) supports this impression for the Deception and IGAN records, while there seems to have been no change from the first to the second half of the Storbreen record. However, it is clear that for the period covered the long-term relationship between the northern hemisphere and Deception records differs fundamentally from the short-term antiphase variations.

The long-term variations in the records from the Antarctic Continent (Fig. 32) on the whole do not show the same variations with time as the IGAN and Deception records. The South Pole record, from 1760 to 1957, shows a statistically significant increase in net balance from the first to the last third of the record (Giovinetto and Schwerdtfeger, 1966). The Byrd record shows a small but persistent decrease in net balance from 1839 to 1954, but no other major changes from 1549 to 1959 (Gow, 1968). No noticeable changes in net balance with time are shown in the record from 1783 to 1956 at Wilkes (Cameron, 1964), from 1855 to 1959 at Little America V (Gow, 1968) or from about 1840 to 1967 at Plateau Station (Koerner, 1971). This lack of correspondence with the IGAN and Deception records is not surprising in view of the differences between the climatic parameters represented in these records and those from the Antarctic Continent.

Table 11. Variance Ratio test for Deception, Storbreen, and IGAN records.

Deception Island

	Mean
Period 1783-1876	+0.039 m
Period 1877-1970	-0.039 m

Variation	Sum of squares	Degrees of freedom	Variance	F
Total	125,226	187		
Between groups	2,820	1	2,820	
Within groups	122,406	186	658	4.29 $P < 0.05$

Storbreen

	Mean
Period 1817-1893	-0.198 m
Period 1894-1970	-0.218 m

Variation	Sum of squares	Degrees of freedom	Variance	F
Total	501,258	153		
Between groups	146	1	146	
Within groups	501,112	152	3,297	0.04 Not signif.

IGAN

	Mean	
Period 1818-1896	+0.072 m	(Data for five years, from 1891 to 1895, are not included)
Period 1897-1970	-0.270 m	

Variation	Sum of squares	Degrees of freedom	Variance	F
Total	1,113,108	147		
Between groups	43,420	1	43,420	
Within groups	1,069,688	146	7,327	5.93 $P < 0.05$

RELATIONSHIP BETWEEN SUMMER TEMPERATURE VARIATIONS AT DECEPTION ISLAND AND OTHER AREAS FOR THE PAST TWO HUNDRED YEARS

It has been shown that mass-balance variations from 1944 to the present at Deception Island are closely related to summer balance and summer degree-day variations. If this relationship also holds true for the pre-1944 variations in net mass balance, this part of the record can be interpreted to indicate summer temperature variations. It is reasonable to assume that because the year-to-year variations in the summer balance exceed those of the winter balance, the long-term variations in summer balance will exceed those in the winter balance. It must be emphasized, however, that this is an untested assumption which is probably only partly true. Changes in temperature are not independent of changes in other meteorological variables, and long-term changes in temperature related to long-term climatic changes are likely also to have been accompanied by long-term changes in, for example, the winter precipitation.

With the above reservation in mind the net mass-balance curve is now interpreted in terms of variations in summer temperatures. The relationship $D = 226.0-193.6\ b_n$, where D is the summer degree-days, gives the best linear fit between degree-days and net balance for the period 1944 to 1967. Assuming that the same relationship holds true for the pre-1944 period, the degree-days for each year can be calculated. In order to carry out comparisons with other areas it is necessary to interpret the degree-days in terms of summer temperatures, as other records normally are given in the form of temperature. The relationship between degree-days and summer temperatures (mean temperatures December-February) is shown in Fig. 33. As expected, the relationship is not linear, as the degree-days are measured over a variable time scale (the period for which temperatures are $> 0°C$), whereas the mean temperatures refer to a constant time period of three months. The empirical relationship shown in Fig. 33 probably applies in the pre-1944 period, and this relationship is used to compute the temperature variations for the whole period.

Figure 34 shows the 10-year running means (binomial smoothing) of degree-days from about 1780 to the present calculated from the net balance record, and the corresponding variations in mean summer temperatures. In view of the assumptions made, it must be emphasized that the temperature shows at best the general shape of the curve of past temperature variations, indicating only the order of magnitude of the temperature changes and not their absolute values. However, the major changes in the curve do probably reflect major changes in temperatures, and a brief examination of how these changes compare with major changes in other parts of the world is in order.

The main features of the temperature record in Fig. 34 are (i) a generally cold period, with a cooling trend, from about 1780 to about

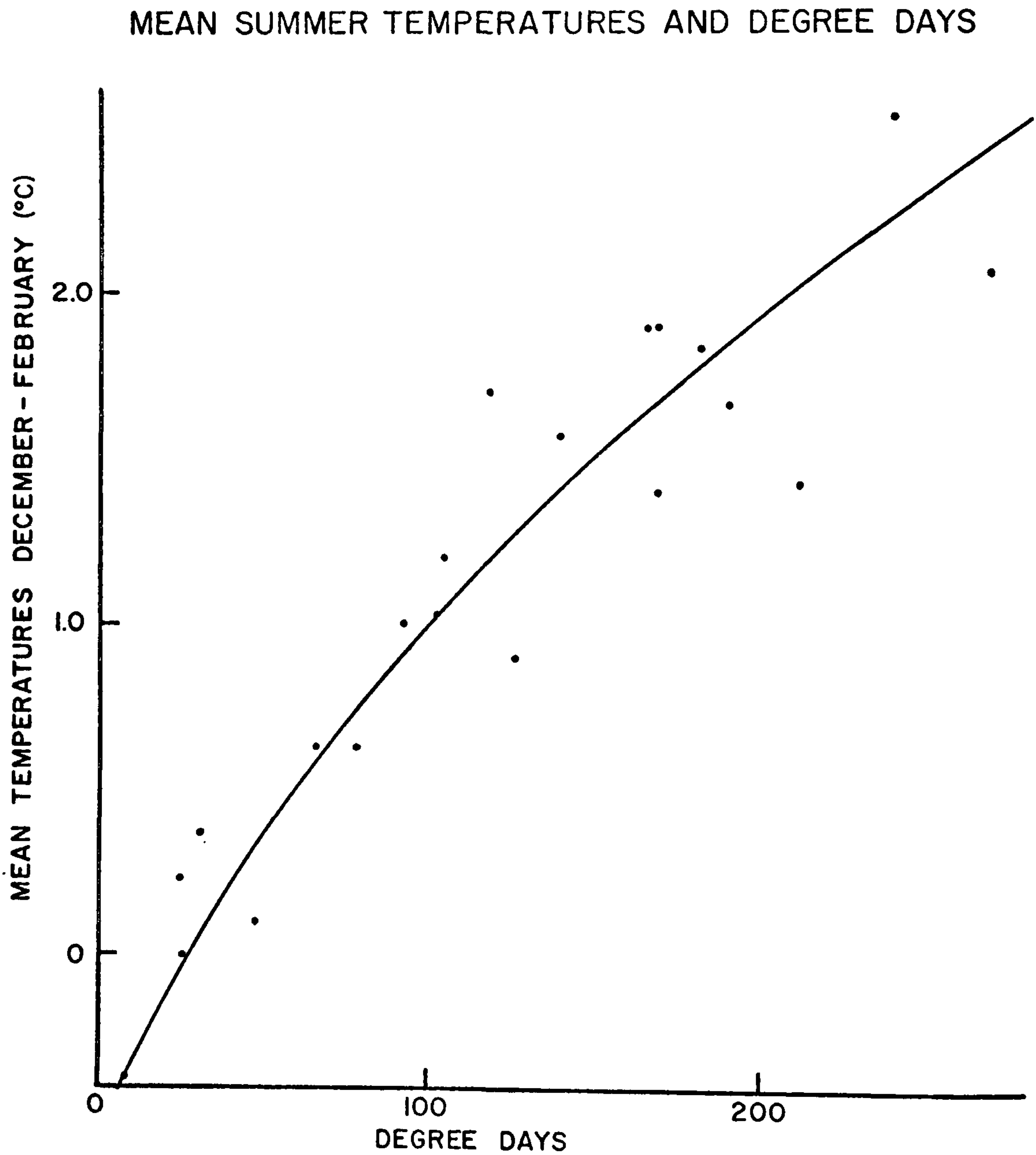

Figure 33. Relationship between mean summer temperatures (December-February) and degree-days for each summer determined by planimetry of the curves of mean monthly temperatures.

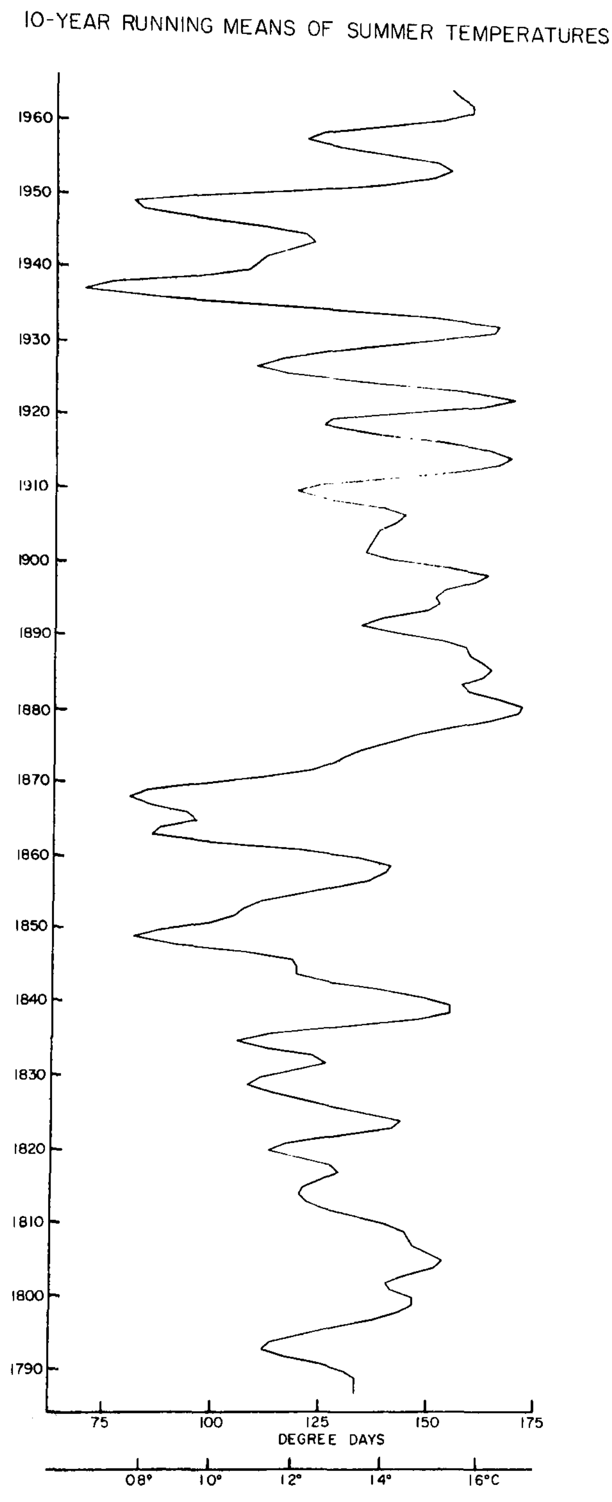

Figure 34. 10-year running means of summer degree-days and mean summer temperatures. The running means are smoothed by the binomial function used for Fig. 16. The temperature values are not precise, and only suggest the order of magnitude and not the absolute amounts of temperature changes over the past two centuries.

1870; (ii) a relatively brief period of marked warming over the period 1870-1880; and (iii) a generally warm period from about 1880 to the present, but with a cold interval from the late 1930's to the early 1950's. In broad terms, these features of lower mean summer temperatures during the past century than in the present century are identical to the relationships established in many other studies. Figure 35 shows the global temperature changes computed by Mitchell (1961) from area-weighted meteorological data, and also two of the many long temperature series available from the northern hemisphere. The latter two curves are typical of most long temperature series published, which are mostly from Europe, and which show that the preceding few centuries were mostly cooler than the present, with the warming trend starting in about 1880, and extending to about 1940.

When Mitchell (1961, 1963) discussed his curves of global temperature changes, he indicated an uncertainty in his conclusion that the warming from 1880 to 1940, and the cooling thereafter, was of global extent. This uncertainty arose because information from the ocean areas and from the high southern hemisphere latitudes was lacking. It is unreasonable to compare the Deception Island record with Mitchell's curves in detail, in view of the uncertainties in the former. It may be concluded, however, that the Deception Island record has significantly extended the area of the globe known to have undergone warming from about 1880 to 1940. There is thus now little reason to doubt that this warming was of global extent.

Mitchell (1963) also suggested that the cooling after about 1940 was planetary in scope, but he could not show it to be statistically significant. The Deception Island record does not provide information to settle this question; there is a marked temperature drop in the record after the late 1930's, but the trend is reversed again in the early 1950's. Such a temperature curve could be obtained by superimposing a short-term (1-2 decades) temperature cycle on a long-term cooling trend that started in the late 1930's. Other interpretations of the curve are possible, however, and more years of observations are needed before this question can be definitely settled.

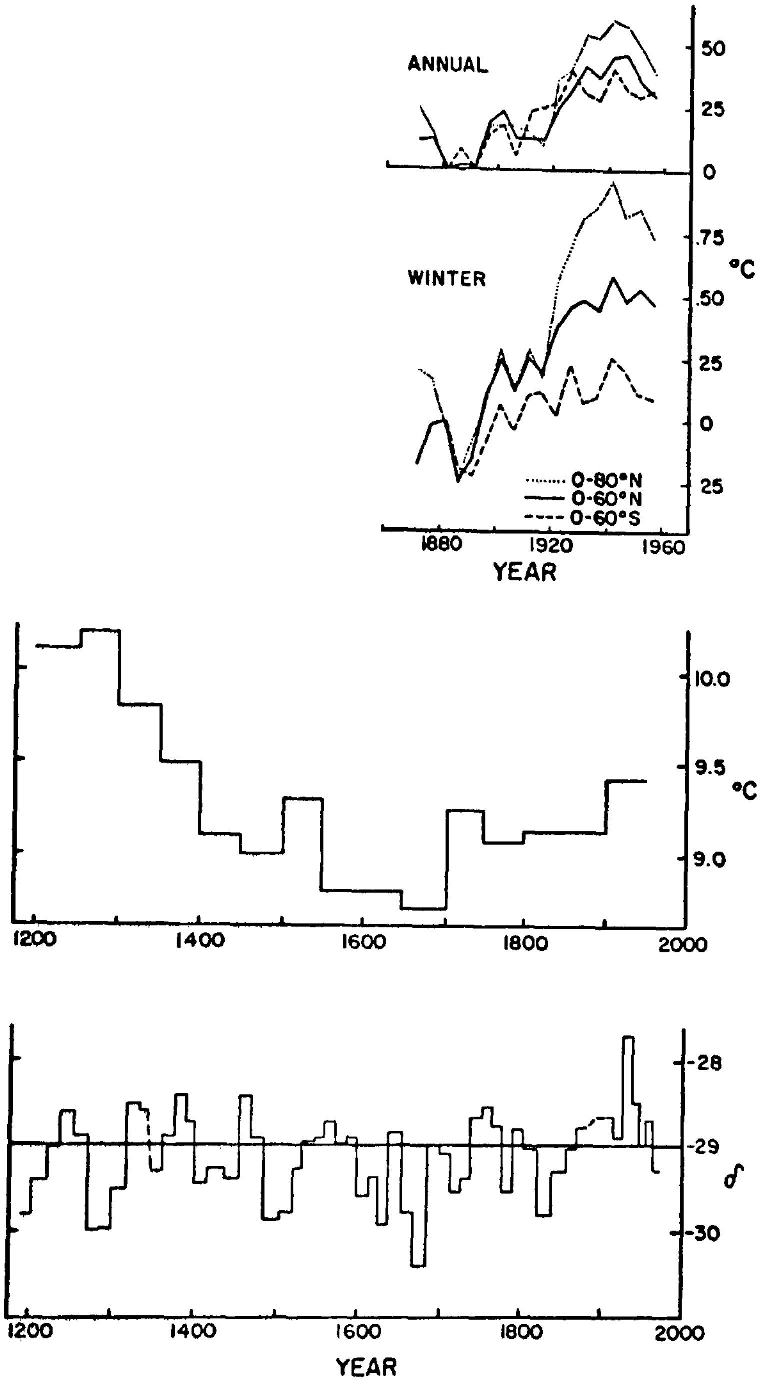

Figure 35. Temperature records from different areas of the world. The top curve is from Mitchell (1961). The middle curve is from Lamb (1965) and shows 50-year means of annual temperatures in England. The bottom curve is from Dansgaard and others (1971) and shows O-18/O-16 δ-values at Camp Century, Greenland.

THE DECEPTION RECORD AND MODELS USED TO EXPLAIN CLIMATIC CHANGES

Brooks (1949) quoted Kipling most aptly:

> "There are nine and sixty ways
> Of constructing tribal lays,
> And every single one of them is right."

and went on to say that there are at least nine and sixty ways of constructing a theory of climatic change. The number of theories proposed up to the present is conservatively estimated at over one hundred. Many of these models are concerned with climatic changes over much longer time periods than the two centuries discussed here, and therefore are not considered below. The models proposed to explain climatic changes over the time period covered by the Deception record are of essentially three different types:

(1) Variation in solar energy output

- i. Variation in effective black-body radiation
- ii. Variation in radiation at selective wavelengths

(2) Variation in fraction of solar energy absorbed

- i. Variation in transmissivity of the earth's atmosphere
  - (a) Dust from volcanic eruptions
  - (b) Variation in CO_2 content
  - (c) Variation in O_3 content
  - (d) Variation in water vapor content and cloudiness
- ii. Variation in albedo of the earth
  - (a) Change of cloud cover
  - (b) Change of surface albedo

(3) Variation in the redistribution of heat over the earth's surface

- i. Change in atmospheric circulation
- ii. Change in ocean circulation

These three kinds of models will have different effects on global climate. Changes in energy output or absorption, with circulation patterns constant, will give rise to changes in global climate that should be more or less the same for the whole earth, whereas changes in circulation patterns without changes in the amount of energy reaching the earth will give rise to contrasting climatic changes in different parts of the earth. Because the atmospheric circulation is chiefly zonal it follows that these contrasting effects should mostly be found between stations separated in latitude.

In reality the three types of models are not independent, and at the present state of knowledge the final effect on climate from changes in any one of these factors cannot be confidently predicted from either theoretical considerations or physical evidence. It is therefore not intended here to evaluate these models in detail. Such evaluations can be found in, for example, Lamb and Johnson (1959), Mitchell (1961), Flohn (1961), and Mitchell (1968). There seems to be general agreement among these and other authors that no single variable can adequately account for all observed climatic changes. On the other hand, there is considerable disagreement in the literature about which models account for the largest proportion of past climatic variations. The lack of theoretical agreement is to a considerable extent caused by a lack of paleoclimatic data by which the various theoretical models may be tested. The Deception Island record has provided paleoclimatic data from a previously unknown region of the globe, and it may therefore be of value to consider whether this new information can assist in discriminating between these models.

Two major conclusions have resulted from the preceding comparisons between the Deception record and records from other areas:

1. The warming trend from the past to the present century was of global extent, whereas this may not have been the case for the post-1940 cooling.

2. Short-period (dominant periods about 1 and about 2 decades) changes in climatic elements affecting the net mass balance on middle- to high-latitude glaciers in the two hemispheres have been out of phase.

The implications of each of these conclusions on the climatic models will not be considered in turn.

The conclusion that the warming from the nineteenth to the twentieth century was of global extent implies that the total energy of the atmosphere has changed. The cause for this is most likely that the total solar energy absorbed has varied, caused by variations in models of type (1) or (2) above. Four of these models are well supported by observational or indirect evidence:

(i) Effective black-body radiation of the sun has increased.

(ii) Solar radiation at selective wavelengths has increased.

(iii) Dust content of the atmosphere has decreased, following decreased volcanic activity.

(iv) CO_2 content of the atmosphere has increased, following increased burning of fossil fuels.

(i) Most workers agree that any change in effective black-body radiation of the sun would directly affect global atmospheric temperatures. However, there are no conclusive direct measurements of such variation, although tentative identification of such variation has been made (Jerzykiewicz and Serkowski, 1968), and indirect evidence for such variations is present (Dansgaard and others, 1971).

(ii) It is not established that variation in the sun's radiation at selective wavelengths can affect the climate of the lower atmosphere. The occurrence of these variations is well established. They primarily occur in the ultraviolet and X-ray frequencies, and are related to the well-known sunspot cycles. But there is no satisfactory model that explains how these variations are translated into variations of the lower atmosphere climate. Many studies, as for example those of Köppen (1914), who related sunspot cycles and temperatures, and the many tree-ring studies, have found highly significant relationships between sunspots and climatic elements. But other authors (Mitchell, 1961; Bryson and Dutton, 1961), testing the same relationships a few decades later, have generally found that the significance of the relationships has disappeared. Many authors have shown that sunspot activity may also have varied in pre-historic time (see Olsson, 1970), but the asertion that these variations are related to climatic variations for the whole post-glacial period (Suess, 1968) is not accepted by all (Damon, 1968).

It is not established whether the variations under (i) and (ii) are independent. If they are independent, there is no evidence by which (i) may be tested, and this remains a speculative hypothesis. If they are related, then the recent global warming supports both hypotheses, as sunspot activity increased from late last century through the period of warming (Mitchell, 1961).

(iii) The relationship between increased explosive volcanic activity, leading to increased atmospheric dust content, and decreased temperatures, particularly in the hemisphere of the eruptions, is well established. It has been extensively discussed most recently by Lamb (1970, 1971). He and others have shown that the global warming trend from late last century coincided with reduced explosive volcanic activity.

(iv) That the CO_2 content of the atmosphere has increased markedly from the end of the last century, following increased burning of fossil fuel, is well established (Callendar, 1958; Bolin and Eriksson, 1959). Increased CO_2 content has a "greenhouse" effect, and will warm the atmosphere.

Thus all these models may explain the warming from about 1880 to 1940. However, only one of the four models can explain the post-1940 cooling, _if_ this has been of global extent. As sunspot activity and

CO_2 content continued to rise after 1940, and as there have been no major explosive eruptions to account for the cooling, it seems that none of these hypotheses are satisfactory for explaining this phenomenon (Mitchell, 1961). The only remaining hypothesis that can explain a global cooling is to assume that the effective black-body radiation of the sun is at least partly independent of the sunspot activity, and that there has been a decrease since 1940. Since this model is the least well supported by the pre-1940 evidence, this suggestion must be considered speculative.

As shown earlier, however, it has not yet been established, with confidence, that the post-1940 cooling was of global extent. Thus, until this has been established, the new information from Deception Island does not effectively discriminate among these four models.

The warming until 1940 may also be explained by other hypotheses, for example by variations of ozone content, water content, or cloudiness, or by increased heat flow from the earth, or by cycles in the turnover of oceanic water masses of different temperatures. These hypotheses are all supported by less evidence than the previous four, and they are not discussed here because, with one exception, the Deception Island record does not provide information that can be used to test them. The exception is the hypothesis advanced by Fletcher (1969), that increased sea-ice cover around Antarctica, with increased albedo and decreased surface air temperatures, should lead to increased vigor of the general circulation. This in turn would cool the tropics, and heat the middle and high latitudes in the northern hemisphere, leading to an antiphase relationship between temperatures in middle to high latitudes in the two hemispheres. For the time scale of the recent global warming (1880 to 1940) this hypothesis is not supported by the Deception Island data.

The short-term relationship between Deception Island and middle- to high- latitude glaciers in the northern hemisphere suggests that cycles exist in the atmospheric circulation, working to redistribute the atmospheric heat content. It is especially interesting to note that the dominant periods in this antiphase relationship are about 11 and 20 years, and that the close agreement of these periods with the sunspot periods suggests that these cycles in the atmospheric (and oceanic?) circulation are driven by energy exchanges tied to the variations in solar activity.

The manner by which the variations in solar activity are translated to the near-surface atmosphere of the globe is presently unknown. It may eventually be observed in a mechanism such as that suggested by Fletcher (1969) and discussed above, or through other cyclic mechanisms in the atmospheric and oceanic circulation. Not until the antiphase relationship found here has been tested by comparison of many climatic stations in the two hemispheres, and an adequate mechanism for transfer of solar variation to the lower atmosphere is found, can the highly speculative idea that solar activity is the cause of the antiphase relationship be properly treated.

SUMMARY

Subglacial volcanic eruptions on Deception Island (63°S, 60° 40'W) in 1969 and 1970 revealed ice stratigraphy in fissures and craters. Annual net mass-balance variations from about 1780 A.D. to the present were determined from this stratigraphy. Annual layers were exceptionally well marked by dirt layers, formed each summer when large amounts of dust are blown onto the glaciers from surrounding areas of loose volcanic material. No dust is deposited on the glaciers in the winter because the island is then completely snow-covered. The sections studied originated high in the accumulation area of the glaciers, and only minor errors in the record are caused by years missed due to zero or negative net balance.

Meteorological data are available from Deception Island for 1944 to 1967; summer degree-days for these years are significantly negatively correlated with stratigraphically determined net mass balances ($r = -0.55$, $P < 0.01$). This correlation generally becomes insignificant when dating of the layers is changed by one or more years and thus provides a confirmation of the stratigraphic technique. The correlation also shows that summer degree-days and summer balances must be closely correlated; year-to-year variations in the summer balances, as represented by the summer degree-days, account for a larger proportion of annual net balance variations than do winter balance variations. Close correlation between summer degree-days and summer balances is supported by heat- and mass-balance results on a selected glacier, G 1, on the island which also agree with the conclusions from other studies. Long records of observed summer and winter balances from three glaciers in Europe indicate that the concept that summer balance variations contribute most to annual net balance variations is of general applicability.

Glacier G 1 was in mass equilibrium for the 1968-1969 balance year but had negative mass balances for the following two years. Shortwave solar radiation contributed most of the heat transfer to the glacier in the summer. Mean gradients with respect to elevation of the summer, winter, and net balance curves are 6, 1, and 7 mm m^{-1} respectively. The term "mean activity index" is proposed for the latter gradient, and its use is suggested in place of Shumskii's "energy of glacierization" and Meier's "activity index".

The stratigraphic studies revealed 23 probable volcanic eruptions. Although these eruptions have changed significantly the mass and heat balance conditions in the ablation area of the glaciers, their effects were not significant in the accumulation areas, where the ash is buried within a year. It is therefore concluded that the mass balance history recorded in these sections is representative of the climatic changes on the island.

Comparisons between summer temperatures at Deception Island and those of 15 other stations in middle to high latitudes in the southern hemisphere show that summer temperature variations at Deception Island are representative of regional variations in the southwest Atlantic Ocean and that the variations are to a lesser degree representative of the variations in the latitude band 55° to 70°S.

Mean mass balances for 5-year intervals, and 5-year running means of balances for Deception Island are significantly negatively correlated with observed mass-balance variations from 1946 in the northern hemisphere, and balances in both hemispheres show a marked cyclicity of about 10 years. The same antiphase relationship, with a cycle of 11 years, and a weaker cycle of about 20 years, is found when the entire Deception record is compared with the precise records, back to 1816, from Storbreen, Norway. The 20-year cycle is also suggested by the comparison between the observed northern hemisphere balances and the Deception Island balances, but cannot be established because of the short period of the data.

The entire Deception Island record shows the same general atmospheric warming from the 19th to the present century, as occurred in the northern hemisphere and in the lower to middle latitudes of the southern hemisphere. There now seems little reason to doubt that the global atmosphere as a whole underwent warming during this period. The cooling after 1940, general in the northern hemisphere, is also suggested in the Deception Island record, but cannot be definitely established.

The above comparisons indicate that models proposed to explain climatic changes must account for a global warming, from late last century to about 1940, and an antiphase cyclic relationship, characterized by dominant periods of about 11 and about 20 years, in the climatic elements that affect glacier mass balances in middle to high latitudes in the two hemispheres.

APPENDIX A

LAYER THICKNESSES, DENSITIES, AND NET MASS BALANCES FOR THE FISSURE AND CRATER RECORDS

FISSURE

Year	Depth at base of layer (m)	Thickness (m)	Density (Mg m^{-3})	Balance (m)	Notes
1970-1971				0.20	Data for the upper
1969-1970				0.43	four years are
1968-1969	1.42			0.45	mostly from surface
1967-1968	2.37	0.95	0.50	0.49	mass balance
1966-1967	3.26	0.89	0.52	0.48	studies, and are
1965-1966	3.95	0.69	0.54	0.37	adjusted for
1964-1965	4.63	0.68	0.56	0.38	refreezing of
1963-1964	5.43	0.80	0.60	0.48	meltwater.
1962-1963	5.88	0.45	0.62	0.28	
1961-1962	6.52	0.64	0.64	0.41	
1960-1961	6.90	0.38	0.65	0.25	
1959-1960	7.80	0.90	0.67	0.60	
1958-1959	8.92	1.12	0.70	0.79	
1957-1958	9.77	0.85	0.71	0.61	
1956-1957	10.30	0.53	0.72	0.38	
1955-1956	11.00	0.70	0.73	0.51	
1954-1955	11.37	0.37	0.73	0.27	
1953-1954	11.78	0.41	0.73	0.30	
1952-1953	12.60	0.82	0.74	0.61	
1951-1952	12.88	0.28	0.74	0.21	
1950-1951	13.78	0.90	0.75	0.68	
1949-1950	14.89	1.11	0.76	0.84	
1948-1949	16.23	1.34	0.77	1.03	
1947-1948	17.11	0.88	0.78	0.69	
1946-1947	17.76	0.65	0.78	0.51	
1945-1946	18.53	0.77	0.79	0.61	
1944-1945	19.15	0.62	0.79	0.49	
1943-1944	19.74	0.59	0.80	0.47	
1942-1943	20.24	0.50	0.80	0.40	

Year	Depth at base of layer (m)	Thickness (m)	Density (Mg m^{-3})	Balance (m)	Notes
1941-1942	21.52	1.28	0.81	1.04	
1940-1941	22.09	0.57	0.81	0.46	
1939-1940	22.54	0.45	0.81	0.37	
1938-1939	23.17	0.63	0.82	0.52	
1937-1938	24.77	1.60	0.83	1.33	
1936-1937	25.92	1.15	0.83	0.96	
1935-1936	26.48	0.56	0.84	0.47	
1934-1935	26.95	0.47	0.84	0.40	
1933-1934	27.19	0.24	0.84	0.20	
1932-1933	27.44	0.25	0.84	0.21	
1931-1932	27.56	0.12	0.85	0.10	
1930-1931	28.35	0.79	0.85	0.67	
1929-1930	28.90	0.55	0.85	0.47	
1928-1929	29.41	0.51	0.85	0.43	
1927-1928	29.99	0.58	0.86	0.50	
1926-1927	30.94	0.95	0.86	0.82	
1925-1926	31.78	0.84	0.87	0.73	
1924-1925	31.90	0.12	0.87	0.10	
1923-1924	32.09	0.19	0.87	0.17	
1922-1923	32.30	0.21	0.87	0.19	
1921-1922	32.58	0.28	0.87	0.24	
1920-1921	32.96	0.38	0.87	0.33	
1919-1920	34.18	1.22	0.88	1.07	
1918-1919	34.50	0.32	0.88	0.28	
1917-1918	34.78	0.28	0.88	0.25	
1916-1917	35.24	0.46	0.89	0.41	
1915-1916	35.36	0.12	0.89	0.11	
1914-1915	35.50	0.14	0.89	0.13	
1913-1914	35.82	0.32	0.89	0.28	Section shifted laterally.
1912-1913	36.33	0.51	0.89	0.45	
1911-1912	36.98	0.65	0.90	0.59	
1910-1911	37.39	0.41	0.90	0.37	
1909-1910	38.78	1.39	0.90	1.25	
1908-1909	38.97	0.19	0.90	0.17	
1907-1908	39.26	0.29	0.90	0.26	
1906-1907	39.62	0.36	0.90	0.22	Thick pyroclastic deposit.

APPENDIX A (Continued)

CRATER

Year	Depth at base of layer (m)	Thickness (m)	Balance (m)	Notes
1914-1915	0.52	0.52	0.47	Constant ice density of 0.9 Mg m^{-3} is used for the crater section
1913-1914	0.59	0.07	0.06	
1912-1913	0.74	0.14	0.14	
1911-1912	1.57	0.83	0.75	
1910-1911	1.62	0.05	0.05	
1909-1910	2.69	1.07	0.96	
1908-1909	2.85	0.16	0.14	
1907-1908	3.15	0.30	0.27	
1906-1907	3.41	0.26	0.23	
1905-1906	4.01	0.60	0.54	
1904-1905	4.70	0.69	0.62	
1903-1904	4.86	0.16	0.14	
1902-1903	5.24	0.38	0.34	
1901-1902	6.30	1.06	0.95	
1900-1901	6.41	0.11	0.10	
1899-1900	6.74	0.33	0.30	
1898-1899	6.91	0.17	0.15	
1897-1898	7.09	0.18	0.16	
1896-1897	7.94	0.85	0.77	
1895-1896	8.19	0.25	0.23	
1894-1895	8.41	0.22	0.20	
1893-1894	8.53	0.12	0.11	
1892-1893	9.48	0.95	0.86	
1891-1892	10.04	0.56	0.50	
1890-1891	10.30	0.26	0.23	
1889-1890	10.46	0.16	0.14	
1888-1889	10.79	0.33	0.30	
1887-1888	11.45	0.66	0.59	
1886-1887	11.53	0.08	0.07	
1885-1886	11.63	0.10	0.09	
1884-1885	12.03	0.40	0.36	
1883-1884	12.65	0.62	0.56	
1882-1883	12.83	0.18	0.16	
1881-1882	13.02	0.19	0.17	
1880-1881	13.21	0.19	0.17	
1879-1880	13.46	0.25	0.23	
1878-1879	13.74	0.28	0.25	

Year	Depth at base of layer (m)	Thickness (m)	Balance (m)	Notes
1877-1878	14.22	0.48	0.43	
1876-1877	14.55	0.33	0.30	
1875-1876	15.04	0.49	0.44	
1874-1875	15.39	0.35	0.32	
1873-1874	16.04	0.65	0.59	
1872-1873	16.54	0.50	0.45	
1871-1872	16.78	0.24	0.22	
1870-1871	17.39	0.61	0.55	
1869-1870	18.58	1.19	1.07	
1868-1869	18.83	0.25	0.23	
1867-1868	19.83	1.00	0.90	
1866-1867	20.96	1.13	1.02	
1865-1866	21.04	0.08	0.07	
1864-1865	21.36	0.32	0.29	
1863-1864	22.87	1.51	1.36	
1862-1863	23.54	0.67	0.60	
1861-1862	23.90	0.36	0.32	
1860-1861	24.44	0.54	0.49	
1859-1860	24.72	0.28	0.25	
1858-1859	25.13	0.41	0.37	
1857-1858	25.47	0.34	0.31	
1856-1857	25.94	0.47	0.42	
1855-1856	27.04	0.58	0.52	0.52 m pyroclastic layer
1854-1855	27.20	0.16	0.14	
1853-1854	28.42	1.22	1.10	
1852-1853	28.55	0.13	0.12	
1851-1852	29.37	0.82	0.74	
1850-1851	29.61	0.24	0.22	
1849-1850	30.69	1.08	0.97	
1848-1849	31.61	0.92	0.83	
1847-1848	32.29	0.68	0.61	
1846-1847	32.40	0.11	0.10	
1845-1846	32.86	0.46	0.41	
1844-1845	33.71	0.85	0.77	
1843-1844	34.08	0.37	0.33	
1842-1843	34.52	0.44	0.40	
1841-1842	34.90	0.38	0.34	
1840-1841	35.06	0.16	0.14	
1839-1840	35.43	0.37	0.33	

APPENDIX A (Continued)

Year	Depth at base of layer (m)	Thickness (m)	Balance (m)	Notes
1838-1839	35.70	0.27	0.24	
1837-1838	35.85	0.15	0.14	
1836-1837	36.23	0.38	0.34	
1835-1836	37.33	1.10	0.99	
1834-1835	37.72	0.39	0.35	
1833-1834	38.33	0.61	0.55	
1832-1833	38.56	0.23	0.21	
1831-1832	38.96	0.40	0.36	
1830-1831	39.39	0.43	0.39	
1829-1830	40.21	0.82	0.74	
1828-1829	40.88	0.67	0.60	
1827-1828	41.01	0.13	0.12	
1826-1827	41.62	0.61	0.55	
1825-1826	42.24	0.62	0.56	
1824-1825	42.42	0.18	0.16	
1823-1824	42.66	0.24	0.22	
1822-1823	42.90	0.24	0.22	
1821-1822	43.32	0.42	0.38	
1820-1821	44.31	0.99	0.89	
1819-1820	44.49	0.18	0.16	
1818-1819	45.14	0.65	0.59	
1817-1818	45.36	0.22	0.20	
1816-1817	45.62	0.26	0.23	
1815-1816	46.32	0.70	0.63	
1814-1815	46.73	0.41	0.37	
1813-1814	47.22	0.49	0.44	
1812-1813	47.55	0.33	0.30	
1811-1812	48.12	0.57	0.51	
1810-1811	48.49	0.37	0.33	
1809-1810	48.69	0.20	0.18	
1808-1809	48.87	0.18	0.16	
1807-1808	49.40	0.53	0.48	
1806-1807	49.71	0.31	0.28	
1805-1806	49.82	0.11	0.10	
1804-1805	50.07	0.25	0.23	
1803-1804	50.31	0.24	0.22	
1802-1803	50.61	0.30	0.27	
1801-1802	51.24	0.63	0.57	
1800-1801	51.40	0.16	0.14	

Year	Depth at base of layer (m)	Thickness (m)	Balance (m)	Notes
1799-1800	51.51	0.11	0.10	
1798-1799	51.94	0.43	0.39	
1797-1798	52.23	0.29	0.26	
1796-1797	52.56	0.33	0.30	
1795-1796	52.90	0.34	0.30	
1794-1795	53.44	0.54	0.49	
1793-1794	53.99	0.55	0.50	
1792-1793	54.40	0.41	0.37	
1791-1792	55.05	0.65	0.59	
1790-1791	55.16	0.11	0.10	
1789-1790	55.57	0.41	0.37	
1788-1789	55.89	0.32	0.29	
1787-1788	56.33	0.44	0.40	
1786-1787	56.61	0.28	0.25	
1785-1786	56.95	0.34	0.31	
1784-1785	57.35	0.40	0.36	
1783-1784	57.68	0.33	0.30	
1782-1783	58.11	0.43	0.39	

There is a progressive error in indicated ages, caused by missing years. Thus the lowest layers are about 6 years older than shown.

APPENDIX B

NORMALIZED MASS-BALANCE RECORD FROM FISSURE AND CRATER

Year	Balance (m)	Notes
1970-1971	-0.330	
1969-1970	-0.099	
1968-1969	-0.077	
1967-1968	-0.035	
1966-1967	-0.043	
1965-1966	-0.152	
1964-1965	-0.140	
1963-1964	-0.038	
1962-1963	-0.236	
1961-1962	-0.104	
1960-1961	-0.263	
1959-1960	0.089	
1958-1959	0.281	
1957-1958	0.103	
1956-1957	-0.126	
1955-1956	0.006	
1954-1955	-0.232	
1953-1954	-0.200	
1952-1953	0.112	
1951-1952	-0.267	
1950-1951	0.185	
1949-1950	0.347	
1948-1949	0.539	
1947-1948	0.201	
1946-1947	0.022	
1945-1946	0.124	
1944-1945	0.006	
1943-1944	-0.012	
1942-1943	-0.081	
1941-1942	0.561	
1940-1941	-0.017	
1939-1940	-0.105	
1938-1939	0.047	
1937-1938	0.858	
1936-1937	0.490	

Year	Balance (m)	Notes
1935-1936	0.002	
1934-1935	-0.066	
1933-1934	-0.265	
1932-1933	-0.253	
1931-1932	-0.361	
1930-1931	0.211	
1929-1930	0.013	
1928-1929	-0.026	
1927-1928	0.046	
1926-1927	0.368	
1925-1926	0.280	
1924-1925	-0.348	
1923-1924	-0.277	
1922-1923	-0.255	
1921-1922	-0.203	
1920-1921	-0.111	
1919-1920	0.631	
1918-1919	-0.158	
1917-1918	-0.186	
1916-1917	-0.024	
1915-1916	-0.322	
1914-1915	-0.145	Values for years 1914-
1913-1914	-0.274	1915 to 1906-1907 are
1912-1913	-0.148	means of fissure and
1911-1912	0.229	crater records
1910-1911	-0.230	
1909-1910	0.667	
1908-1909	-0.282	
1907-1908	-0.171	
1906-1907	-0.209	
1905-1906	0.089	
1904-1905	0.170	
1903-1904	-0.309	
1902-1903	-0.108	
1901-1902	0.504	
1900-1901	-0.346	
1899-1900	-0.144	
1898-1899	-0.293	
1897-1898	-0.282	
1896-1897	0.329	

APPENDIX B (Continued)

Year	Balance (m)	Notes
1895-1896	-0.210	
1894-1895	-0.239	
1893-1894	-0.328	
1892-1893	0.423	
1891-1892	0.064	
1890-1891	-0.205	
1889-1890	-0.294	
1888-1889	-0.133	
1887-1888	0.158	
1886-1887	-0.361	
1885-1886	-0.340	
1884-1885	-0.069	
1883-1884	0.133	
1882-1883	-0.266	
1881-1882	-0.255	
1880-1881	-0.254	
1879-1880	-0.193	
1878-1879	-0.172	
1877-1878	0.009	
1876-1877	-0.120	
1875-1876	0.021	
1874-1875	-0.098	
1873-1874	0.173	
1872-1873	0.034	
1871-1872	-0.195	
1870-1871	0.136	
1869-1870	0.657	
1868-1869	-0.182	
1867-1868	0.490	
1866-1867	0.611	
1865-1866	-0.338	
1864-1865	-0.117	
1863-1864	0.954	
1862-1863	0.195	
1861-1862	-0.084	
1860-1861	0.087	
1859-1860	-0.152	
1858-1859	-0.031	
1857-1858	-0.090	
1856-1857	0.021	
1855-1856	0.122	

APPENDIX B (Continued)

Year	Balance (m)	Notes
1854-1855	-0.257	
1853-1854	0.704	
1852-1853	-0.275	
1851-1852	0.347	
1850-1851	-0.172	
1849-1850	0.579	
1848-1849	0.440	
1847-1848	0.221	
1846-1847	-0.288	
1845-1846	0.023	
1844-1845	0.384	
1843-1844	-0.055	
1842-1843	0.016	
1841-1842	-0.043	
1840-1841	-0.242	
1839-1840	-0.051	
1838-1839	-0.140	
1837-1838	-0.239	
1836-1837	-0.038	
1835-1836	0.614	
1834-1835	-0.025	
1833-1834	0.176	
1832-1833	-0.163	
1831-1832	-0.012	
1830-1831	0.019	
1829-1830	0.370	
1828-1829	0.231	
1827-1828	-0.248	
1826-1827	0.183	
1825-1826	0.194	
1824-1825	-0.205	
1823-1824	-0.144	
1822-1823	-0.143	
1821-1822	0.018	
1820-1821	0.529	
1819-1820	-0.200	
1818-1819	0.232	
1817-1818	-0.157	
1816-1817	-0.126	
1815-1816	0.275	
1814-1815	0.016	

APPENDIX B (Continued)

Year	Balance (m)	Notes
1813-1814	0.087	
1812-1813	-0.052	
1811-1812	0.159	
1810-1811	-0.020	
1809-1810	-0.169	
1808-1809	-0.188	
1807-1808	0.133	
1806-1807	-0.066	
1805-1806	-0.245	
1804-1805	-0.114	
1803-1804	-0.123	
1802-1803	-0.072	
1801-1802	0.230	
1800-1801	-0.199	
1799-1800	-0.238	
1798-1799	0.053	
1797-1798	-0.076	
1796-1797	-0.035	
1795-1796	-0.024	
1794-1795	0.157	
1793-1794	0.168	
1792-1793	0.039	
1791-1792	0.260	
1790-1791	-0.229	
1789-1790	0.042	
1788-1789	-0.037	
1787-1788	0.074	
1786-1787	-0.075	
1785-1786	-0.013	
1784-1785	0.038	
1783-1784	-0.021	
1782-1783	0.070	

There is a progressive error in indicated ages, caused by missing years. Thus the lowest layers are about 6 years older than shown.

APPENDIX C

MASS BALANCE OF GLACIER G 1 FOR 25-m ELEVATION INTERVALS

1968 - 1969

Elevation (m a.s.l.)	Area (m^2)	B_n (m^3)	b_n (m)
> 400	1 600	1 000	0.62
375 - 400	78 900	41 800	0.53
350 - 375	45 700	24 700	0.54
325 - 350	40 100	20 400	0.51
300 - 325	40 300	13 700	0.34
275 - 300	31 100	300	0.01
250 - 275	31 400	1 900	0.06
225 - 250	52 800	- 9 000	-0.17
200 - 225	26 300	-19 500	-0.74
175 - 200	33 000	-32 700	-0.99
150 - 175	17 900	-20 200	-1.13
125 - 150	15 100	-20 300	-1.34
< 125	3 600	- 5 800	-1.62
	417 800	- 3 700	-0.01

APPENDIX C (Continued)

1969 - 1970

Elevation (m a.s.l.)	Area (m^2)	B_w (m^3)	b_w (m)	B_s (m^3)	b_s (m)	B_n (m^3)	b_n (m)
> 400	1 600	1 600	0.99	-500	-0.29	1 100	0.70
375 - 400	78 900	48 800	0.62	-24 400	-0.31	24 400	0.31
350 - 375	45 700	38 400	0.84	-20 600	-0.45	17 800	0.39
325 - 350	40 100	44 100	1.10	-23 300	-0.58	20 800	0.52
300 - 325	40 300	29 400	0.73	-27 000	-0.67	2 400	0.06
275 - 300	31 100	11 500	0.37	-24 600	-0.79	-13 100	-0.42
250 - 275	31 400	26 700	0.85	-23 800	-0.76	2 900	0.09
225 - 250	52 800	37 000	0.70	-63 400	-1.20	-26 400	-0.50
200 - 225	26 300	15 800	0.60	-45 500	-1.73	-29 700	-1.13
175 - 200	33 000	18 800	0.57	-68 600	-2.08	-49 800	-1.51
150 - 175	17 900	7 200	0.40	-47 500	-2.65	-40 300	-2.25
125 - 150	15 100	9 800	0.65	-40 800	-2.70	-31 000	-2.05
< 125	3 600	3 800	1.05	- 9 800	-2.73	- 6 000	-1.68
	417 800	292 900	0.70	-419 800	-1.00	-126 900	-0.30

APPENDIX C (Continued)

1970 - 1971

Elevation (m a.s.l.)	Area (m^2)	B_w (m^3)	b_w (m)	B_s (m^3)	b_s (m)	B_n (m^3)	b_n (m)
> 400	1 600	700	0.41	-500	-0.29	200	0.12
375 - 400	78 900	28 400	0.36	-25 200	-0.32	3 200	0.04
350 - 375	45 700	19 200	0.42	-16 500	-0.36	2 700	0.06
325 - 350	40 100	20 500	0.51	-20 100	-0.50	400	0.01
300 - 325	40 300	23 400	0.58	-30 600	-0.76	- 7 200	-0.18
275 - 300	31 100	16 500	0.53	-30 500	-0.98	-14 000	-0.45
250 - 275	31 400	15 100	0.48	-33 000	-1.05	-17 900	-0.57
225 - 250	52 800	29 100	0.55	-69 700	-1.32	-40 600	-0.77
200 - 225	26 300	7 600	0.29	-45 000	-1.71	-37 400	-1.42
175 - 200	33 000	10 300	0.31	-61 400	-1.86	-51 100	-1.55
150 - 175	17 900	3 900	0.22	-37 900	-2.12	-34 000	-1.90
125 - 150	15 100	3 300	0.22	-35 000	-2.32	-31 700	-2.10
< 125	3 600	700	0.20	- 9 500	-2.64	- 8 800	-2.44
	417 800	178 700	0.43	-414 900	-0.99	-236 200	-0.56

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